Final report – Amsterdam Flexpower Operational Pilot

a detailed analysis of the effects of applying a static smart charging profile for public charging infrastructure.

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Subtitle: A detailed analysis of the effects of applying a static smart charging profile for public charging infrastructure.

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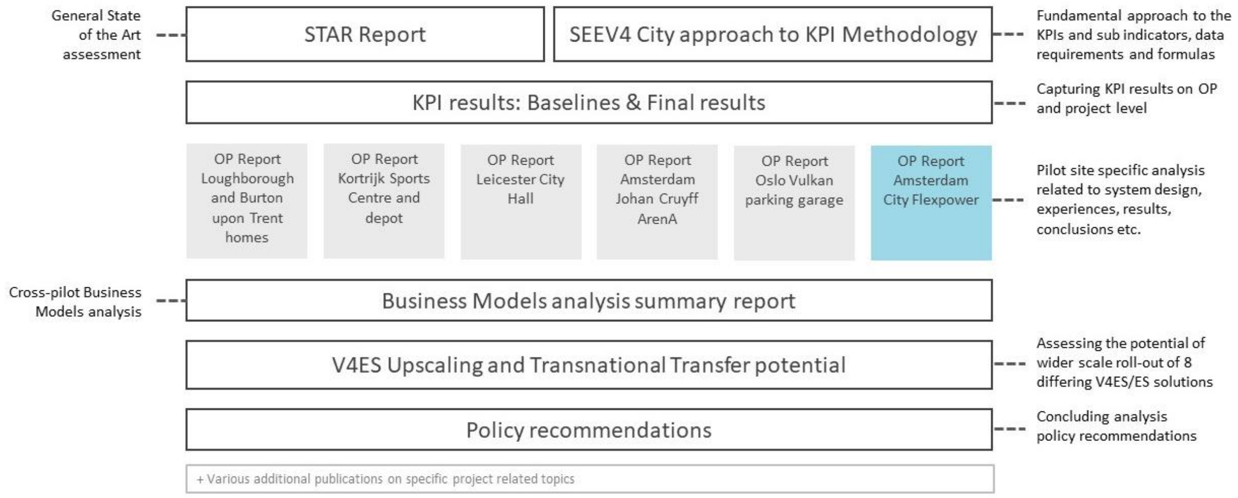
Executive Summary

This report provides a final report of the SEEV4-City Operational Pilot in Amsterdam municipality, The Netherlands. It is part of a collection of reports published by the project covering a variation of specific and cross-cutting analysis and evaluation perspectives and spans 6 operational pilots. This report is dedicated to the analysis of the pilot itself. Below an indication of the set of repots is provided, including an indication where this OP report fits in.



This Vehicle-to-City (V2C) Operational Pilot, Flexpower, was deployed in two phases in Amsterdam from the beginning of March 2017 up to the end of May 2020 [1]. The first phase, defined as Flexpower 1, ran from March 2017 until end August 2018. The second phase, Flexpower 2, encompasses May 2019 – May 2020. The pilot is based on the architecture of the low voltage distribution system in Amsterdam, which is managed by Liander. Improving the utilisation rate of the electrical network is one of the goals of this project. The Flexpower pilot is not about the installation of new equipment but about using a smarter way to use it to push the limits of the system. The Flexpower pilot was used to test, improve and scale a smart charging solution which reduces the power available for charging EVs when the stress on the electricity network is already high and then allow faster charging when the available capacity is sufficient. For this purpose, capacity profiles were created.

The KPI results are summarised in the table below. It reflects the fact that the eventual design choice for the Operational Pilot shifted to a smart charging focus to reduce peak demand on the grid. Therefore, it was not able to meet Key Performance Indicator (KPI) targets for KPI A (CO_2 reduction) or KPI B (Energy Autonomy) as no BSS or PV capacity were added. Although it is possible to adjust the profile to include charging power variations to align with (local) RE generation during day-time hours, the current focus of the pilot was to realize grid deferral by peak demand reduction (KPI C) in evenings. While KPI C is stated as a national target, for the Flexpower OP an average reduction in peak demand of -1.1 kW was achieved per evening per charge point. Because of this it can be determined that €47.000 of grid investment was avoided.

This shows that the Flexpower V2C solution's potential as applied in this pilot is primarily beneficial when scaled to a larger number of charge points on national levels, particularly for areas with limited grid capacity and EV charging growth.

Flexpower Operational Pilot – KPIs			
KPI		***Target***	***Results***
A	CO_2 Reduction	10 – 20 tons	0.33 kg/MWh (-0.07%)
	Sub-KPI: ZE km increase factor	(sub-KPI) ZE km increase factor: 2.9	N/A
B	Energy Autonomy increase	From 10 to 25 % --> Increase 15 %	N/A
C	Grid Investment deferral (by peak demand reduction)	The maximum peak power should be reduced.	Average peak reduction of 470 kW per evening

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Glossary

Abbreviations	Terms
BEV	Battery electric vehicle
PHEV	Plugin hybrid electric vehicle
CCGT	Combined cycle gas turbine
CCS	Combined charging system
C-Rate	Battery charging/discharging rate relative to its maximum capacity
ESS	Energy storage system
EV	Electric vehicle
FFR	Firm frequency regulation
FIT	Feed-in tariff
ICE	Internal combustion engine
ICT	Information and communication technology
KPI	Key performance indicator
LCOE	Levelized cost of energy
LV	Low voltage
NPV	Net present value
OCGT	Open cycle gas turbine
OCPP	Open Charge Point Protocol
OEM	Original equipment manufacturer
OLEV	Office of Low Emission Vehicles
OSCP	Open Smart Charging Protocol
PV	Photovoltaic
SoC	State of charge
USD	US dollar
V2G	Vehicle to grid
V2H	Vehicle to home
V4ES	Vehicle for energy service

1. About the pilot

1.1. Background

1.1.1. Local context and Energy Profile

In 2012, 2.100 battery electric vehicles (BEV) had been sold in The Netherlands. The following year saw the introduction of the plug-in hybrid electric vehicle (PHEV). Since then, the number of electric vehicles (EVs) has been growing, reaching a total of more than 203.000 on the Dutch roads in 2019 (Figure 1).

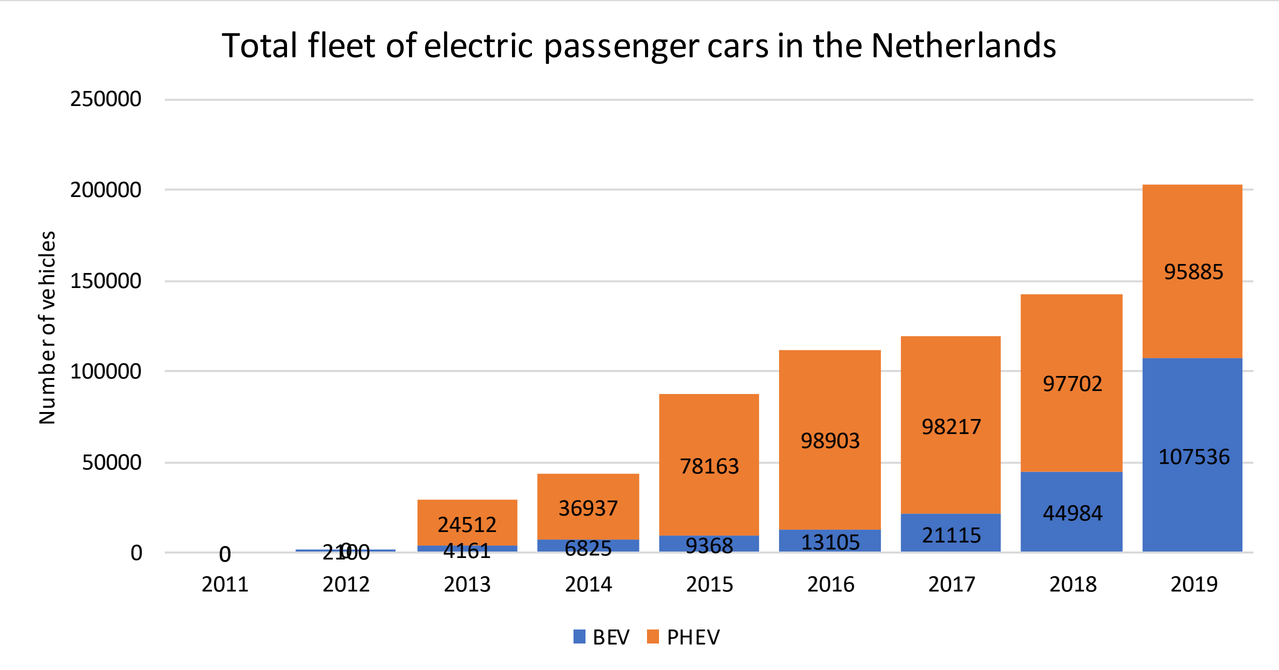

Figure 1: Number of passengers EVs in The Netherlands [2].

In line with this growth, the city of Amsterdam set up the ambition in 2015 to have as much zero-emission traffic as possible by 2025 [3]. Facilitating electric mobility by rolling out public charging infrastructure has been a key strategy, leading to a number of 2600 of public charge points available for EVs by 2020.

The Flexpower pilot was deployed in two phases in Amsterdam from the beginning of March 2017 up to the end of May 2020 [4]. The first phase, defined as Flexpower 1, ran from March 2017 until end August 2018. The second phase, Flexpower 2, encompasses May 2019 – May 2020.

During Flexpower 1, data from 102 charging stations across Amsterdam was collected involving around 8208 unique users and 43904 charging sessions.

To allow for a comparison, the charging stations were separated into two groups for a split-run testing. 50 of the charging stations were configured with a constant capacity profile. On these stations, the current was limited to 25 A per phase on the grid connection during the entire day. These stations are considered as reference stations and are identical to a standard charging station in Amsterdam.

The other 52 charging stations are configured with a flexible capacity profile. Outside of the peak hours, which are defined from 7:00 to 8:00 and 17:00 to 20:00, the current is 35 A per phase, a value higher than the reference stations. During the morning and evening peak hours, the current is limited to 6 A per phase [5].

Flexpower 2 is more than an extension of the Flexpower 1 pilot, with an ultimate increase in the number of charging stations to 432. The profile becomes dynamic with a daily update linked with the expected sun intensity. When unrestricted, the current is set to 32 A. During a sunny day, the current is kept at 32 A per phase from 7:00 until 18:00. On cloudy days, it becomes 25 A per phase. During the peak hours, from 18:00 to 21:00, the current is limited to 8 A.

In this report both the Flexpower 1 and 2 pilots were used to perform technical analysis, identify lessons learned, and extract policy recommendations. Given the sheer size of Flexpower 2 (as compared to Flexpower 1) it was decided to base the quantified analysis (chapter 4) and results for Key Performance Indicators (chapter 5) on the Flexpower 2 project alone. More (quantitative details on the Flexpower 1 pilot can be found in [5]

Amsterdam provides a perfect environment for large-scale innovative pilots like this one, given that a relatively high share of next generation battery EVs (BEVs) are present (e.g. Tesla Taxis operating at Schiphol airport) and that a relatively limited share of households in Amsterdam have a private parking lot. Users therefore depend largely on public charging points.

1.1.2. Local partners

The Flexpower pilot is supported by six partners:

- City of Amsterdam
- Nuon-Vattenfall, energy provider and Charge Point Operator (CPO) in Amsterdam
- Liander, local grid operator
- Amsterdam University of Applied Sciences
- ElaadNL, knowledge and innovation centre in the field of smart charging infrastructure in The Netherlands
- Interreg North Sea Region through the SEEV4City project: subsidy provider

1.2. Objectives and SEEV4-City KPI targets

The SEEV4-City project uses three key performance indicators (KPIs), namely energy autonomy, CO_2 emission savings and grid investment deferral, to measure the environmental and economic benefits. In the case of Amsterdam, the Flexpower project applies Smart Charging and aims mainly to reduce grid impact (KPI C) and reduce CO_2 emissions (by matching charging demand with renewable energy generation).

For the SEEV4-city Flexpower pilot, the KPIs are shown in Table 1.

Table 1: SEEV4-city Flexpower KPIs

Flexpower Amsterdam – KPIs		
KPI		*target*
A	CO_2 Reduction	10 – 20 tons
		(sub-KPI) ZE km increase factor: 2.9
B	Energy Autonomy increase	From 10 to 25 % --> Increase 15 %
C	Grid Investment deferral (by peak demand reduction)	The maximum peak power should be reduced.

1.3. Pilot V4ES solution building blocks

The pilot is based on the architecture of the low voltage distribution system in Amsterdam. The low voltage electrical network is managed by Liander. It is composed of medium to low voltage transformers. On these transformers, 6 to 8 three phase cables are connected. On each cable around 40 households and (at current level) 1 or 2 charging stations are connected.

Improving the utilisation rate of the electrical network is one of the goals of this project. Indeed, the electric network was designed several decades ago, obviously without taking into consideration EVs. The increasing number of EVs creates an extra load (Figure 2, top) on top of the household evening peak. It can potentially create an overload and even instability in the grid. To prevent this instability and increase the utilisation rate of the grid, the charging of EVs can be shifted in time to another moment when the network demand is lower (Figure 2, bottom). Looking forward, the energy contained in the EV batteries could be used to support the local network during the high demand periods using vehicle to grid technology.

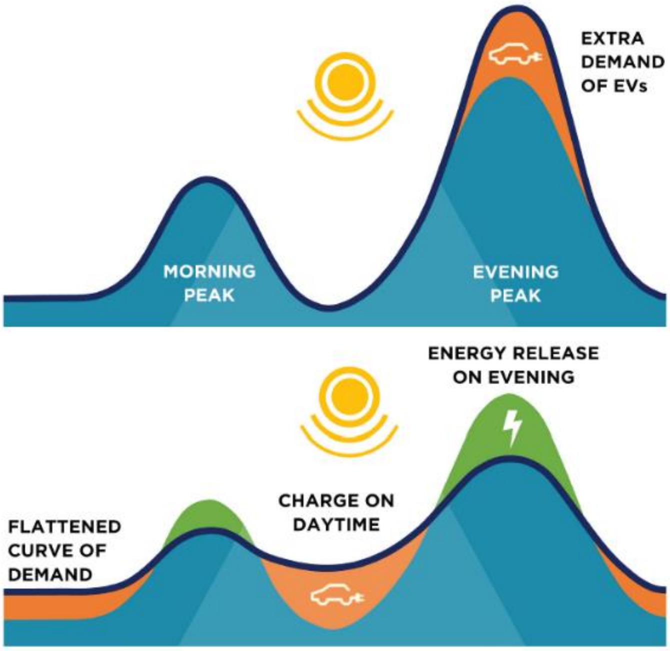

Figure 2: Energy peak during the day and demand shifting.

The Flexpower pilot is not about the installation of new material but a smarter way to use it to push the limits of the system. Figure 3 shows the majors components of the pilot.

The system is composed of:

- A server, collecting the forecast weather data and create the daily individual profile for each charging station.
- The local low voltage network, distributing the energy to the buildings and the charging stations.
- The vehicles, using the charging stations to charge their batteries.

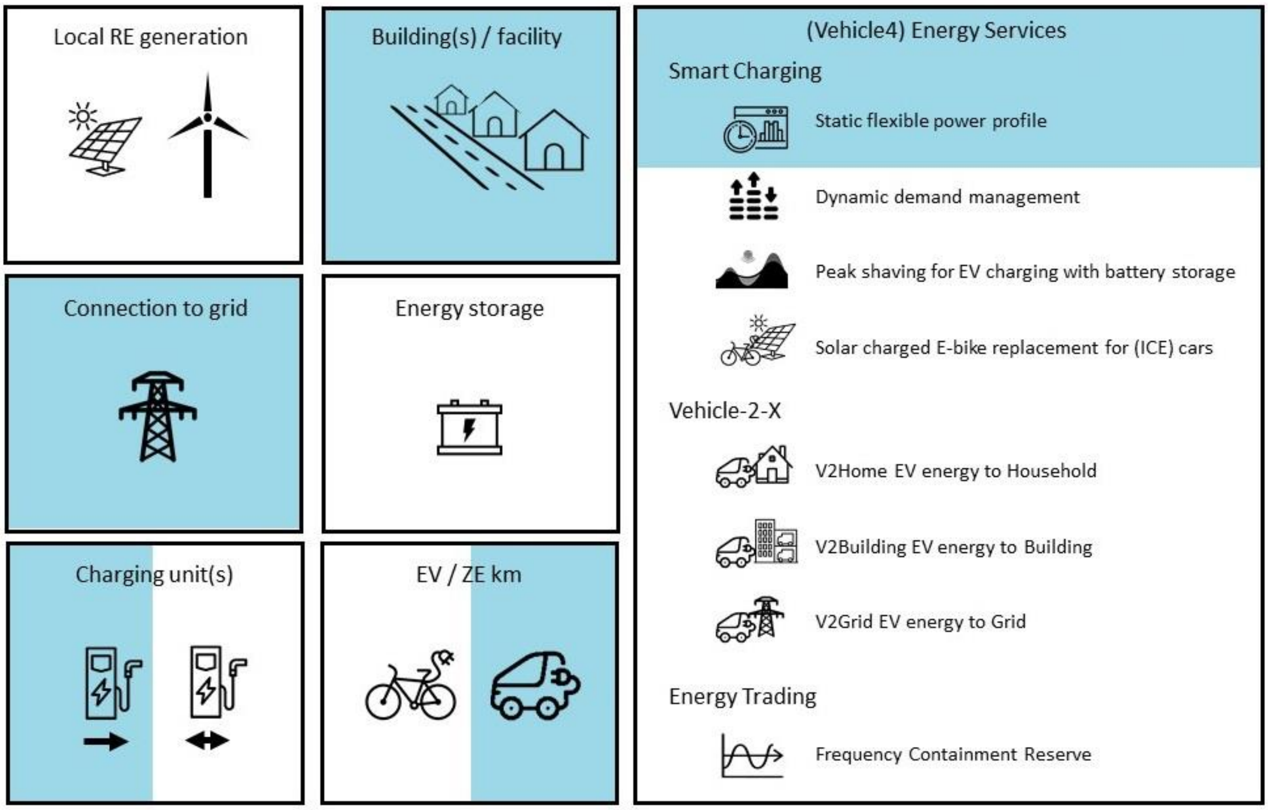

Figure 3: Pilot schematic – system design components

1.4. Household energy usage data

In the Netherlands, Liander made 80 household profiles available [6] of the electricity consumption for the year 2013. The daily average with a 15 minutes resolution is shown as a green line in Figure 4.

As a matter of comparison, the average power used by the reference charging stations applied in the Flexpower 2 pilot (with a constant 25 A current limitation per phase) is superimposed to the consumers ones. It is plotted in yellow.

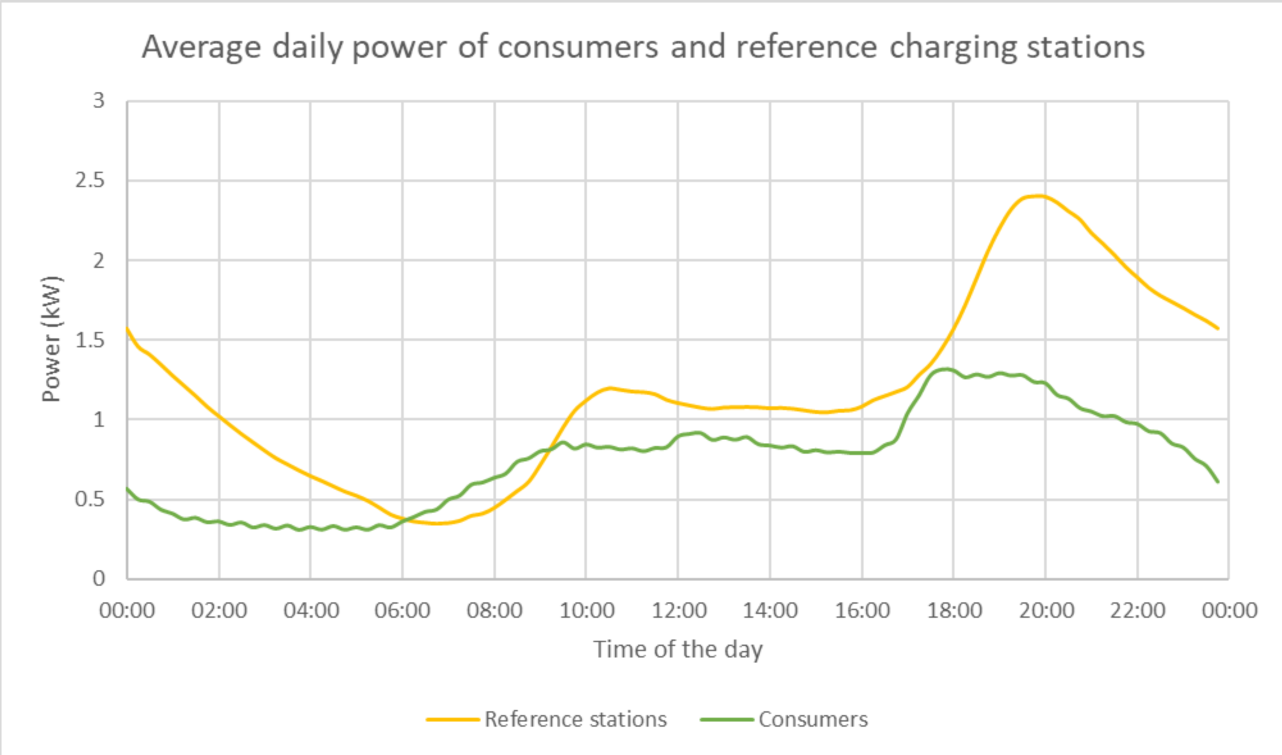

Figure 4: Daily consumption energy profile in The Netherlands based on the aggregated data of 10000 households (green line), compared with the average power delivered by the reference charging stations (in yellow) [6]

The morning and evening peaks are visible in green in Figure 4. During the night, the energy consumption drops to 0.3 kW. At 6:00 the electricity consumption increases up to 10:00 to reach 0.8 kW. After 16:00, the evening peak starts, reaching a level of 1.3 kW around 18:00. Finally, the consumption drops from 22:00 to reach the night level.

Figure 4 also shows, in yellow, the average power delivered by the reference charging stations used in the Flexpower 2 pilot. From midnight to 5:00, the value drops as vehicles are reaching full battery status. The minimum is to be found between 6:00 and 8:00, then is rises again until 10:00. From this time to 16:00, the value is relatively stable, around 1.1 kW.

During the peak evening, from 17:00 to 22:00, the average power demand from the charging stations is equivalent to 2 households. With the increase of the number of EVs, a stress on the electric network can be expected, giving the purpose of the Flexpower pilot.

1.5. System design

This section gives some technical details about the charging infrastructure installed in the city of Amsterdam. The publicly available "Making sense of the Data" document provides a deeper investigation [7].

1.5.1. Single phase power

In an electrical system, the power is defined by the product of the voltage (U) and current (I), and for AC circuits also with power factor (pf).

$$P = U \cdot I \cdot pf$$

As chargers are designed to operate at unity pf, we take pf =1. A vehicle connected to the low voltage network with a maximum charging current of 16 A will charge at a maximum power of:

$$P = 230 \cdot 16 = 3680\ W \approx 3.7\ kW$$

1.5.2. Multiple phases power

The formula above can be generalised for a system with N phases and becomes, with U the phase voltage:

$$P = N \cdot U \cdot I$$

A three phases electric vehicle connected to the low voltage network with a maximum charging current of 16 A will charge at:

$$P = 3 \cdot 230 \cdot 16 = 11040\ W \approx 11\ kW$$

1.5.3. Power and energy

As explained further in chapter 2.2, the data collected by the charging stations contains energy data. This energy needs to be converted to average power to pursue the investigation.

The relation between energy, power and the interval (in minutes) is defined by:

$$E = P \cdot \frac{Interval}{60} \Leftrightarrow P = E \cdot \frac{60}{Interval}$$

1.5.4. Charging stations

The operational pilot makes uses of the publicly available charging station installed in Amsterdam. The particular charging stations installed are "PublicLine" stations, developed by company EVBox [8]. From the 2600 charging stations in Amsterdam, 432 Are selected to receive the Flexpower profile. The other remaining stations are also used as reference stations. Both Flexpower as reference stations are coupled to the low voltage electrical grid via a three-phases connection.

In the reference stations configuration, the grid connection is 25 A and each connector of the charging station is limited to 16 A. The control system allows the charging of the vehicle by closing the contactor associated to each connector. Between these two sockets, there is a phase rotation, allowing simultaneous charging of two single-phase vehicles with maximum power. The charging station is also able to detect if a single-phase vehicle is connected to one connector and 2 phases on the other. In this case, the current is also limited as if two single phase vehicles were connected. The phases rotation is illustrated in Figure 5.

Consequently, for the reference stations, the maximum power available is 11 kW (230 Vx16 Ax3) if a single vehicle is connected and 8.6 kW (230 Vx12.5 Ax3) in case of dual occupancy.

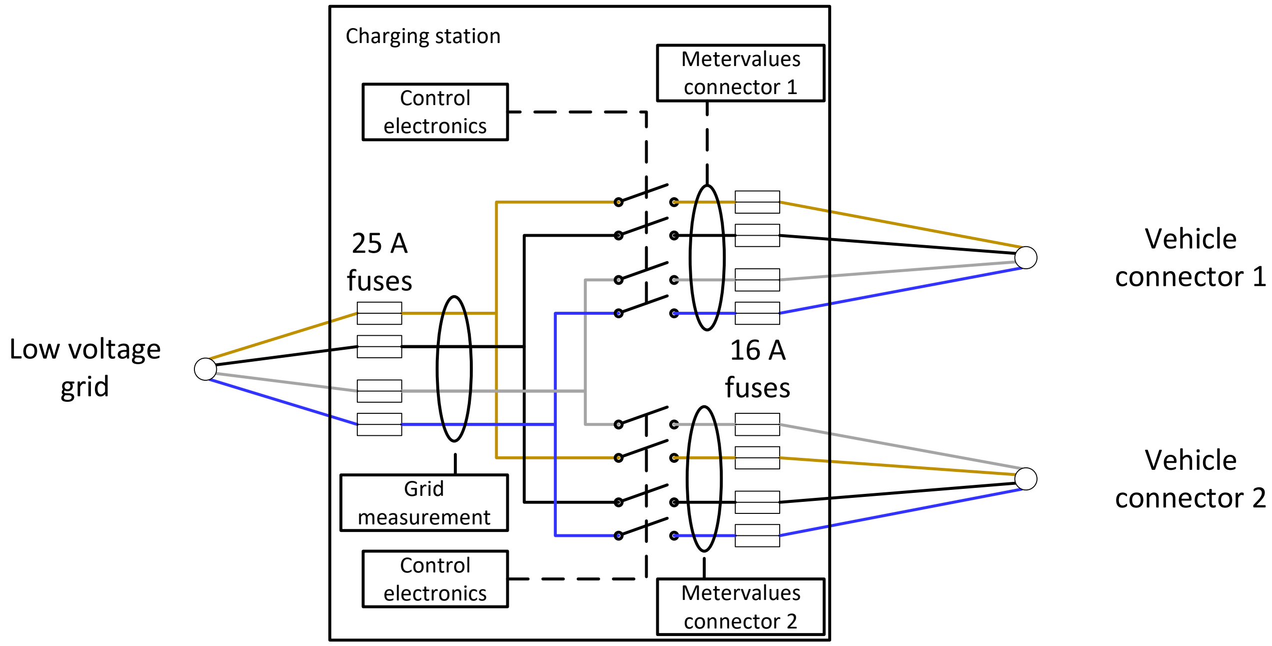

Figure 5: Protections and phases rotation for the reference charging stations. The wire's order is shifted between the connector 1 and 2.

In the Flexpower configuration, Figure 6, the phase rotation is the same, but the maximum protection current on the grid connection is upgraded to 35 A and each socket can deliver up to 32 A.

With the Flexpower station, the maximum power available is 22 kW (230 Vx32 Ax3) if a single vehicle is connected and 11 kW (230 Vx16 Ax3) in case of dual occupancy (and thus higher than for the reference station) if the connected vehicles can handle it.

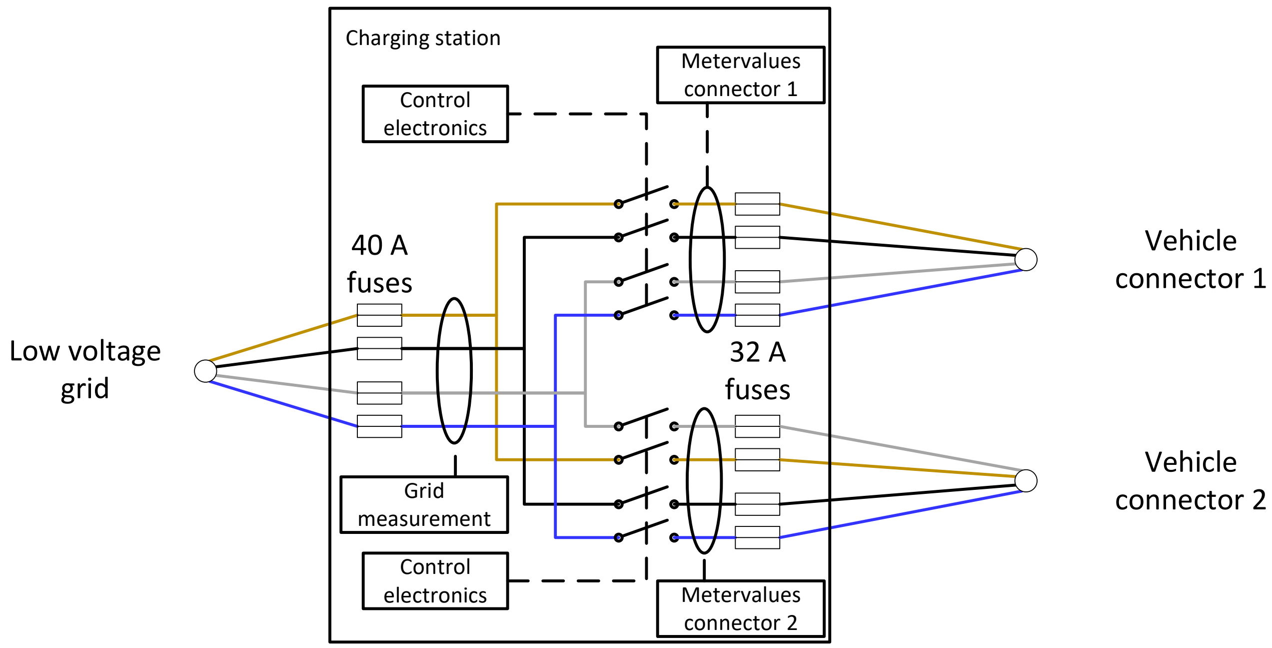

Figure 6: Protections and phases rotation for the Flexpower 1 charging stations

1.5.5. Share of power

The power or current share between the two sockets of the charging stations is made according to the "4 phases rules". If 4 or more phases are connected to the sockets, the current is shared. Otherwise the full current is available. Because the reference and Flexpower limitations are different, they have their respective tables.

Table 2 and Table 3 provides respectively overviews of the different configurations in the reference and Flexpower stations. The voltage and current are considered nominal. The occupancy and vehicle's phase configuration will influence the current share and the related nominal power the vehicle can charge.

The grid columns show the power the network connection point delivers and the percentage of the maximum power it represents.

Table 2: Expected current, power and load factors in different configurations on the reference charging stations. Note that the current is shared between the sockets when 4 or more phases are connected to the station.

Profiles	Connectors							Grid	
	Occupancy		Sum phases	Current (A)		Power (kW)		Power (kW)	Load factor
	1	2		1	2	1	2		
Reference	1	Free	1	16	0	3.7	0	3.7	21%
	1	1	2	16	16	3.7	3.7	7.4	43%
	1	2	3	16	16	3.7	7.4	11.1	64%
	1	3	4	12.5	12.5	2.9	8.6	11.5	67%
	2	Free	2	16	0	7.4	0	7.4	43%
	2	2	4	12.5	12.5	5.8	5.8	11.6	67%
	2	3	5	12.5	12.5	5.8	8.6	14.4	83%
	3	Free	3	16	0	11	0	11	64%
	3	3	6	12.5	12.5	8.6	8.6	17.2	100%

Table 3: Expected current, power and load factors in different configurations on the Flexpower charging stations. Note that current is shared between the sockets when 4 or more phases are connected to the station.

Profiles	Connectors							Grid	
	Occupancy		Total phases	Current (A)		Power (kW)		Power (kW)	Load factor
	1	2		1	2	1	2		
Flexpower	1	Free	1	32	0	7.4	0	7.4	31%
	1	1	2	32	32	7.4	7.4	14.8	61%
	1	2	3	32	32	7.4	14.7	22.1	92%
	1	3	4	17.5	17.5	4	12.1	16.1	67%
	2	Free	2	32	0	14.7	0	14.7	61%
	2	2	4	17.5	17.5	8.1	8.1	16.2	67%
	2	3	5	17.5	17.5	8.1	12.1	20.2	84%
	3	Free	3	32	0	22.1	0	22.1	92%
	3	3	6	17.5	17.5	12.1	12.1	24.2	100%

From the Table 2 and Table 3, it is clear that more power is available to the EV users for the Flexpower stations.

The tables can be used for researchers who are interested to know how a configuration of charging EVs will behave on public charging stations such as the reference stations and Flexpower stations.

1.5.6. Daily profiles

As explained in the chapter 0, the main purpose of the Flexpower pilot is to experiment smart charging by reducing the power available for the charge of the EVs when the stress on the electricity network is already high and allow faster charging when the available capacity on the network is high. For this purpose, capacity profiles were created. In this section we will focus on the profile applied in Flexpower 2 as this is only a slight alteration of the profile applied in Flexpower 1 (for Flexpower 1 we refer to our [5]).

In case of single occupancy (when only one of the two sockets on the charging station is occupied), the Flexpower 2 profile limits the current drawn from the low voltage network with the following pattern:

- From midnight to 6:30, the current is limited to 35 A per phase.
- From 6:30 to 18:00, two cases are possible:
    - Sunny day: the current is limited to 35 A per phase.
    - Less than 30% sun (cloudy day): the current is limited to 25 A per phase.
- From 18:00 to 21:00, the current is limited to 8 A per phase.
- From 21:00 to midnight: the current is limited to 35 A per phase.

The patterns are graphically presented in Figure 7.

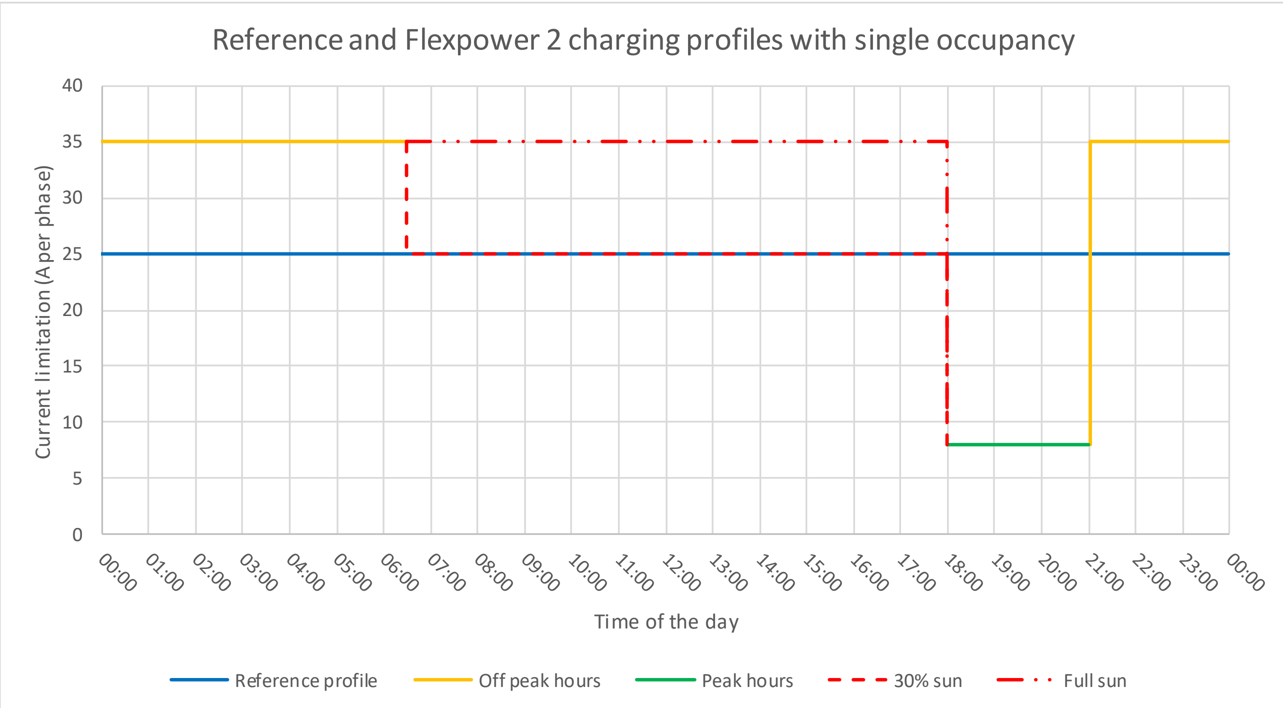

Figure 7: Reference and Flexpower 2 profiles

In case of double occupancy, when both sockets are occupied, the current is shared between the two sockets according to the 4 phases rules as explained in the chapter 1.5.5 Table 3.

The current sharing patterns applied with the 4 phases rules are graphically presented in Figure 8. To facilitate comparison, the scale is the same as Figure 7.

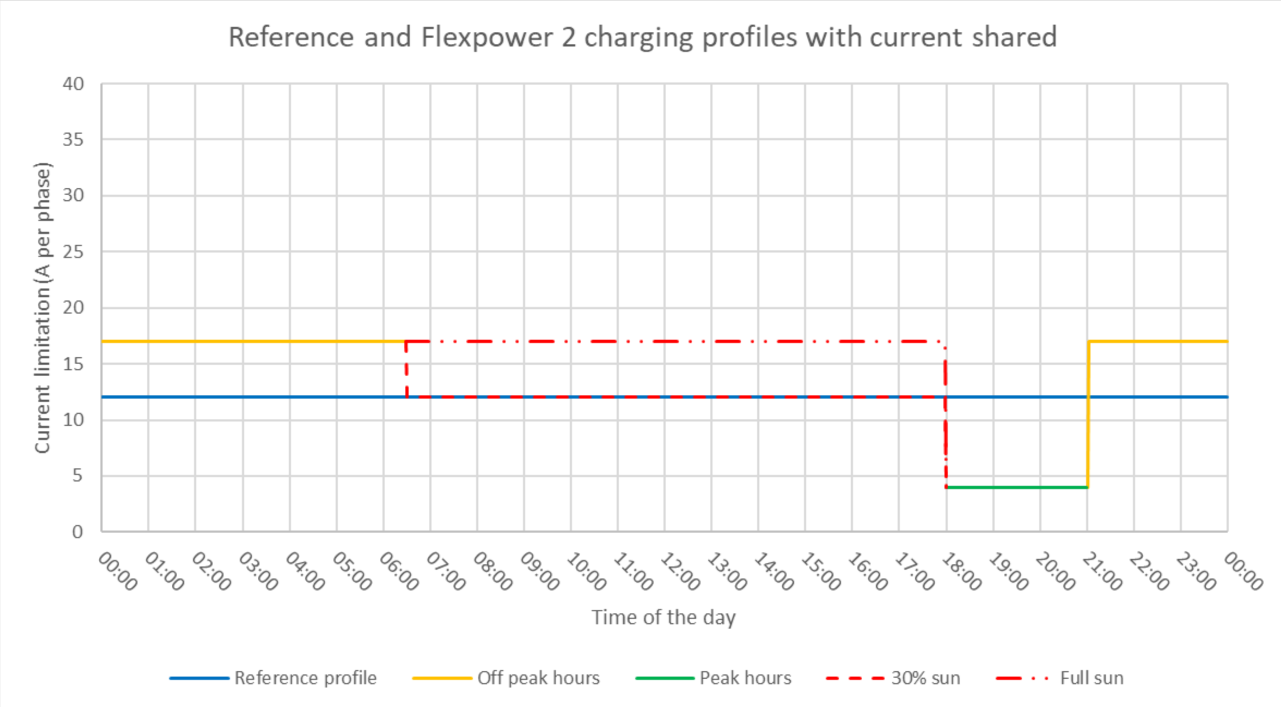

Figure 8: Reference and Flexpower 2 charging profiles with current shared.

Starting on May 5th, 2019, the profiles are generated by ElaadNL on a daily basis based on the weather forecast for the next day. To allow some flexibility and experimentation, each charging station receives an individual profile.

The profiles give the current limitations for the connection to the low voltage network. Most important for the local grid operator is to ensure that the power used by the charging station is equal to or below the capacity profile as shown in Figure 7 and Figure 8.

1.5.7. Current limitation from the vehicle

The charging current is limited by the charging station but also by the embedded charger in the vehicle. From the information collected from the ev-database website[9], three main current categories are identified and reported in Table 4.

Table 4: Identified nominal charging currents for EVs.

EV Database current (A)	Categories current (A)
14	16
16	
20	25
24	
29	32
31	
32	

These categories will be used further in this document to identify the vehicles.

1.5.8. Charging power of EVs

From the categorisation in section 1.5.7 and the phase configurations found in the ev-database, the vehicles are grouped in 6 categories according to their nominal charging powers and currents. These categories are shown in Table 5.

Table 5: Power for various currents limits and phase configuration.

Current (A)	1 Phase	2 Phases	3 Phases
16	3.7 kW	7.4 kW	11 kW
25	-	-	17 kW
32	7.4 kW	-	22 kW

Further investigation has shown that the category 32 A with three phases category represents less than 1% of the vehicles. This category has been merged with the 3 phases 25 A (17 kW).

1.6. Objectives for this study

Figure 3 illustrates the peak demand during evening times and underlines the importance of carrying out operational pilots like Flexpower to reduce the impact of EV charging during evening times. Flexpower is specifically designed to reduce this evening loads by temporarily reducing the charging speed. In order to compensate, Flexpower provides a premium power during off peak times, thereby providing a temporary bonus-malus system. The key for this study was to establish the effects of this Flexpower profile for:

- actual grid impacts during peak times
- possible higher matching with renewable energy generation during daytimes
- consumer impacts (positively or negatively affected in terms of charge volumes
- business case implications (in terms of charge volumes per charging station)

2. Data collection and processing

2.1. Assumptions and research questions

2.1.1. Assumptions

In conducting the evaluation of the Flexpower pilot the following key assumptions were made:

- The charging stations are separated in two comparable groups. One group is using the Flexpower profile whereas the reference group is not profiled (and has a constant current limit).
- all EVs using the public charging stations in Amsterdam are considered, including habitual, frequent users as well as non-habitual users (e.g. visitors).
- It is assumed that each RFID represents one unique EV, which is considered fair for the vast majority of EVs.
- In case an EV does not charge anymore, the session is considered to be complete and the EV fully charged.
- The user behaviour is assumed not to have changed with the introduction of Flexpower. In other words, EV drivers are assumed not to either prefer or avoid Flexpower stations. This is confirmed in our user research [10].

2.1.2. Research Questions

The following research questions were assessed during the evaluation of the Flexpower project.

1. Technical feasibility and scalability
   a. How can differences in charging characteristics between (PH)EVs by explained?
   b. Fault detections: Which errors were found in the data used; and can these errors be explained and prevented?
   c. Simulation model: How can charging behaviour on a group of charging stations be modelled taking into account double occupancy and different charging capabilities of EVs?
2. Measurable effects of Flexpower on users
   a. Which percentage of users are affected by the Flexpower profile (positively or negatively)?
   b. What is the effect of applying Flexpower on the charging time and charging volume?
   c. To what extent does Flexpower stations attract EV users or prevent EV users to charge there?
3. Impact on the low voltage network
   a. What is the impact of Flexpower on reduction of the peak in the evening?

2.2. Data collection, selection and processing

2.2.1. Data collection

Two datasets were used for the Flexpower analyses: the transaction data and the meter values.

The **transaction dataset** contains the Charging Data Record (CDRs). For each charging session, it comprises the start time, end time, duration and total energy of the transaction, as well as the RFID of the user. This data is automatically sent to the CHIEF database each week, which is managed by the AUAS / HvA. More information on this dataset can be found on the IDO-laad website [11].

The transaction data does not have enough resolution for the Flexpower analysis. For example, a transaction with a duration of 4 hours and total energy of 44 kWh could have been achieved by non-stop charging at 11 kW, or by charging at 22 kW for 2 hours and waiting for 2 more hours because the battery was already full.

To address this issue, we also use the meter value data, which contains the value of the meter in the connector (in units of Wh) for every 15 minutes during charging, and for every 2 hours during connection without charging. To distinguish these two scenarios, a more detailed data set is required, the meter values.

The **meter values** are the actual meter readings which are stored in 15 minutes intervals relative to the start of a transaction. The measures are made by the charging station independently for each connector. The meter values are also sent to the AUAS / HvA and available in a database via a secured interface.

The meter values alone are also not sufficient to do the analysis for two reasons. First, the dataset does not contain RFID information, which allows us to connect different transactions by the same user. Second, the meter values do not cover the full charging session. The first meter value (first green stick on the left in Figure 9) is sent 15 minutes after the start of the transaction (first red stick on the left in Figure 9) and the last meter value (last green stick on the right) is sent some time before the end (last red stick on the right). This means the start and end times cannot be matched between the two datasets. Moreover, the difference between the last and the first meter value is often slightly smaller than the total energy found in the transaction data (since some energy is loaded in the first 15min and in the last couple of minutes).

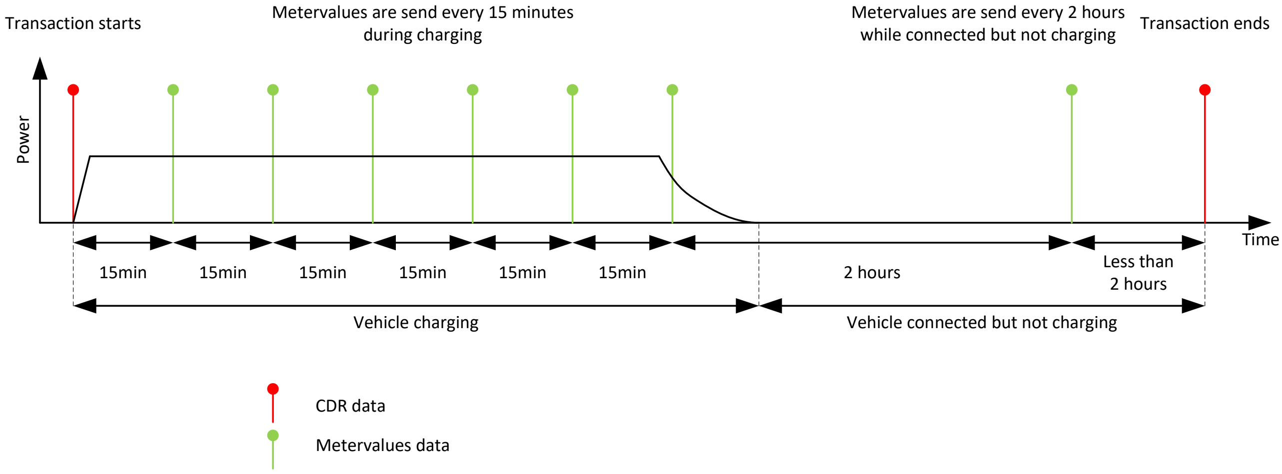

Figure 9: CDR and meter values data transmitted

Unfortunately, the two datasets do not have a shared transaction ID column which can be used for merging. And because the datasets do not have an overlapping start time, end time or total energy there is no single unique property to use as a match between the two datasets. The merge was performed by finding the transaction that has a start time *before* the first meter value of the session and an end time *after* the last meter value on the corresponding connector and charging station. This gave a 97% match. The difference can be explained by the removal of several records in the data cleaning stages (section 2.2.2).

2.2.2. Data selection

Not all the data collected during the period were identified as valid or useful. Consequently, before doing any analysis, some filtering was required. The filtering is made by using the following steps:

- If only one meter value is recorded for the transaction, it is not possible to compute the power, since this is done by taking the difference of multiple measured energy values.
- No vehicle can be charged with a power higher than 50 kW or the energy cannot be recovered from the vehicle (negative power). Transactions which contain these properties cannot be real events.
- Some transactions have zero energy transferred.
- The largest size available for a battery is 90 kWh [12]. Any transaction showing more than 120 kWh has been removed as it is not realistic (sometimes this is the sum of small amounts of charging over a period of weeks).
- For some transactions, it was not possible to find a matching RFID. These transactions are also discarded.

The count of the filtered transactions is shown in the Table 6.

Table 6: Overview of removed data records.

Numbers of Transactions	Removed Transactions	Explanation
269480	-	Raw number of transactions
215053	54427	Removing weekends
194487	20566	Transaction with only one meter value
193537	950	Transactions with charging > 50 kW or negative charging
179678	13859	Transaction that do not charge at all (total energy = 0) or charge > 120 kWh
175691	3987	Transactions with a gap of > 4h in the meter values

About 35% of the transactions recorded was not usable and thus removed from the analysis.

This filtered data is used for the data analysis.

2.3. *Current sharing*

Figure 10 is experimental evidence of the previous explanation from chapter 1.5.5. Sessions were identified with a different combination of vehicles on the sockets. To simplify the read, data were selected when the current limitation on the grid connection is 25 A. The expected powers are:

Table 7: Possible combinations found in Figure 10.

<table>
<tr><th>Current (A)</th><th>Phases</th><th>Power (kW)</th><th>Description</th></tr>
<tr><td rowspan="3">12.5</td><td>1</td><td>2.9</td><td>Single phase vehicle with three phases</td></tr>
<tr><td>2</td><td>5.8</td><td>Two or three phases vehicles together.</td></tr>
<tr><td>3</td><td>8.6</td><td>Three phases vehicle</td></tr>
<tr><td rowspan="2">16</td><td>1</td><td>3.7</td><td>Single phase vehicle with a single or two phases</td></tr>
<tr><td>2</td><td>7.4</td><td>Two phases vehicles</td></tr>
<tr><td>25</td><td>1</td><td>5.8</td><td>32 A single phase vehicle</td></tr>
</table>

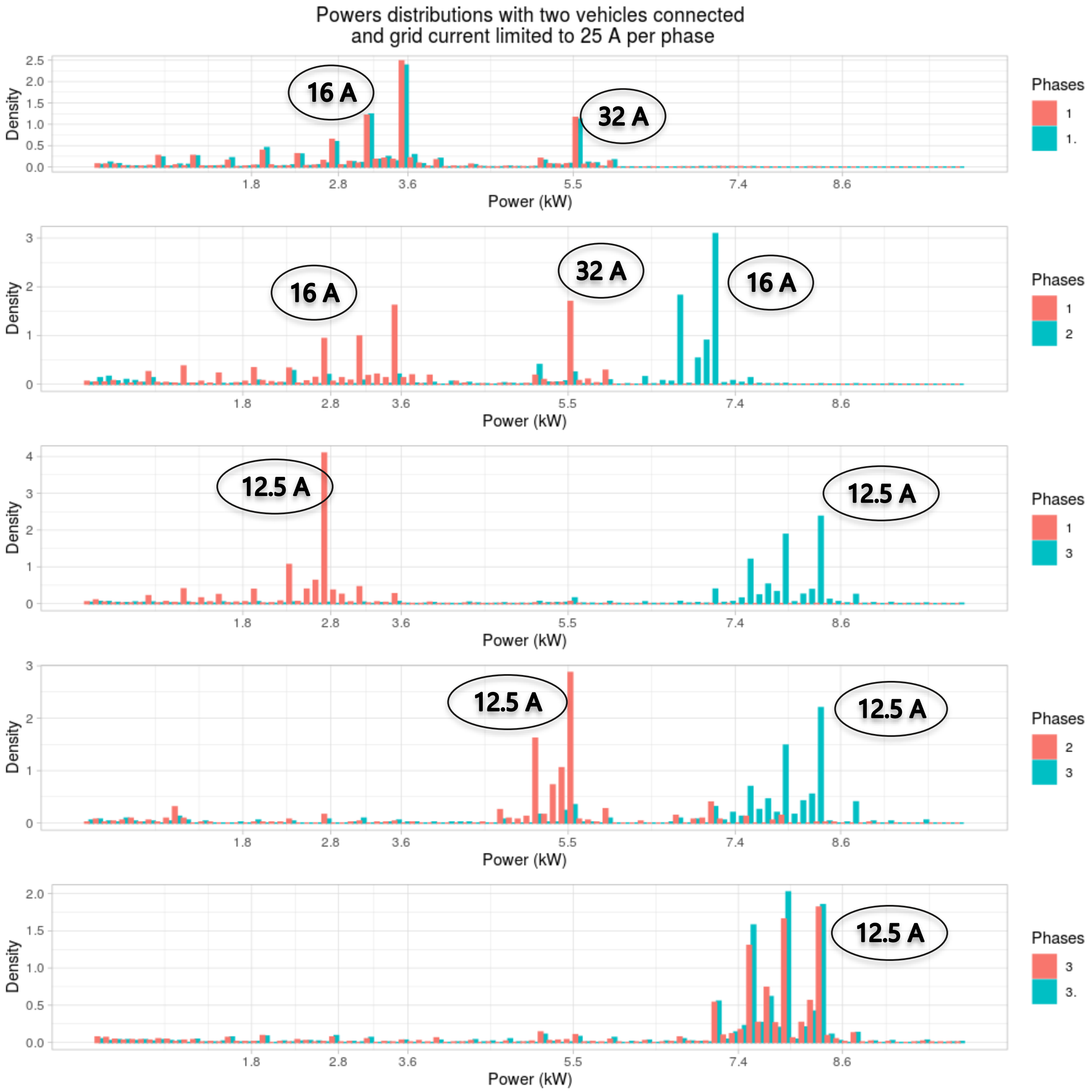

Figure 10: Illustration of the 4 phases rule. The charging power is nominal on the two first plots (1 and 2 phases). The current is shared on the three last plots, when the total number of phases connected is? 4 or more.

Figure 11 shows how the current is always shared between the two sockets when two vehicles are connected. The red distribution plot shows some values at high powers (11 kW and 17 kW), but the green one is absent at these high values. It demonstrates that the current is always shared between the two sockets, even if the second vehicle is in idle mode.

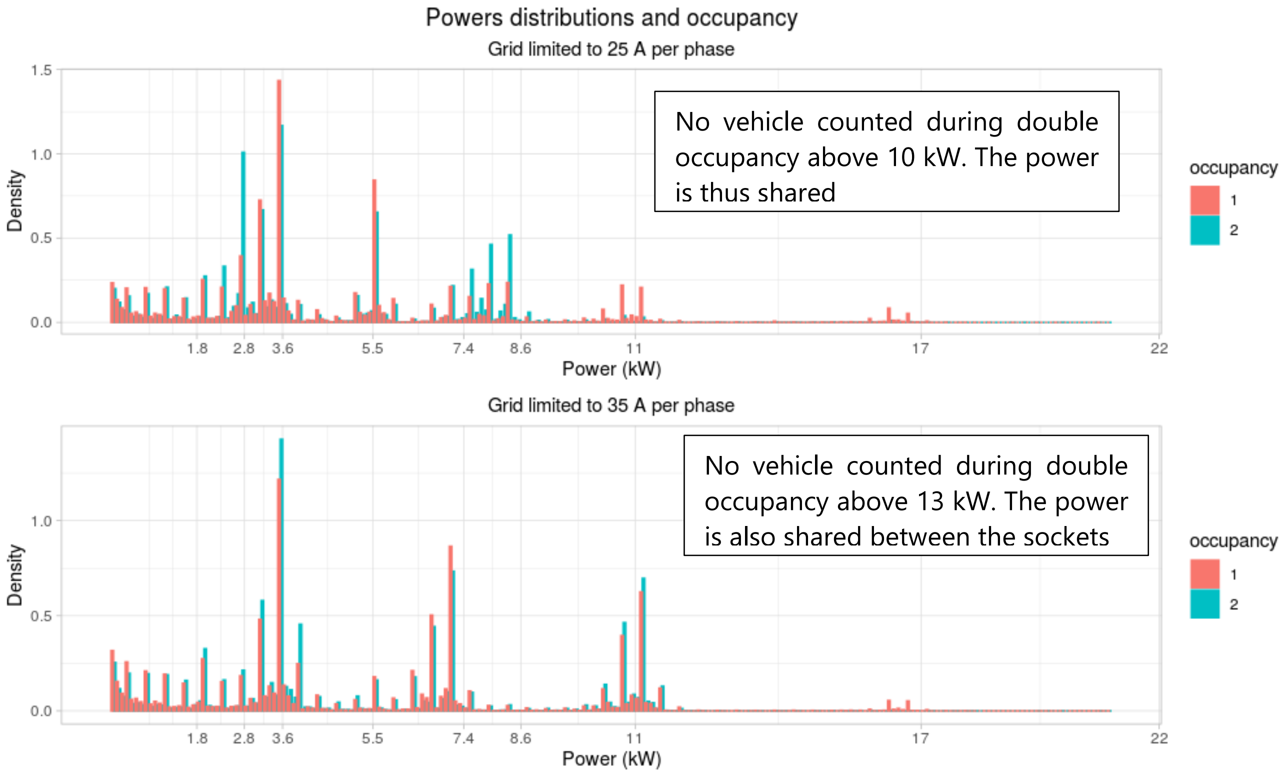

Figure 11: Distribution of the power charged by an EV in different configurations. The power is shared between the two sockets, even if the second vehicle is in idle mode.

2.4. Alternating charging

On the Flexpower stations, the minimum current allowed during the peak hours is 8 A per phase in the case of a single occupancy. If more than 4 phases are connected to the charging station, the current is shared between the two sockets. The lowest current defined by the IEC 61851-1 is 6 A per phase. To be able to charge with 4 A per charging socket, the charging station applies alternating charging.

Alternating charging refers to keeping the current to 8 A per phase for one socket, while the second socket is put in idle with a current of 0 A. This setup is sustained for 15 minutes. At the end of the interval, the socket configurations are switched, also for 15 minutes. The cycle continues until at least one vehicle does not charge anymore.6 A

This way, the average current charged by a vehicle is 4 A even is the nominal current is 8 A. During the experiment, it has been found that some EVs were unable to exit the idle mode and restart the charging. Investigations on this phenomenon showed that the IEC 61851-1 norm was not always implemented correctly.

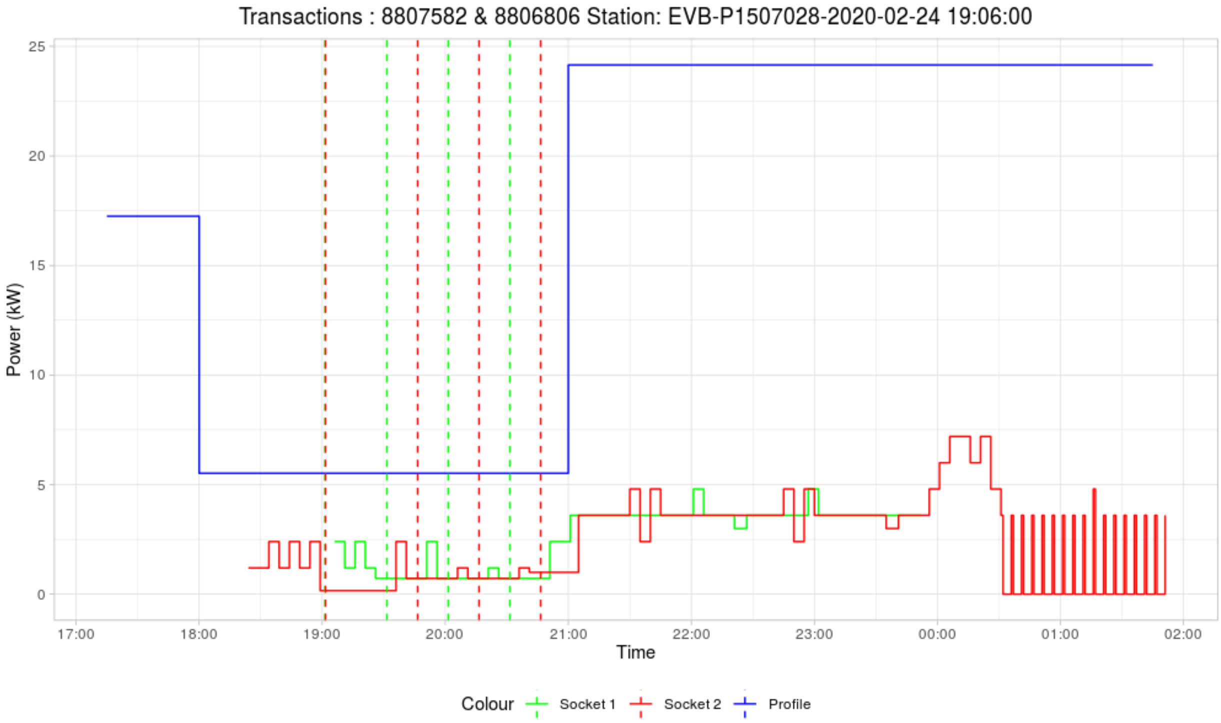

Figure 12: Example of alternating charge. Two vehicles are simultaneously connected to a charging station. During the restricted period, the current values alternates between the two sockets. The value does not go down to 0 because the measured period is not synchronised with the actual current. The energy and thus the power are averaged on the time interval.

2.5. *Vehicles identification*

To evaluate the impact of the Flexpower pilot on the various categories of vehicles, defined in Table 5, vehicles need to be classified based on the data.

2.5.1. General

The vehicles are allocated to the categories in Table 5, with the exception that the 22 kW category is merged with the 17 kW because the group because it is very small. Together they represent the group of 3-phase vehicles that can charge with currents above 16 A.

For each interval in the meter values, the average power is computed and interpreted if possible. Figure 13 shows an example of the power distribution on Flexpower stations during single occupancy and when the 25 A current limit was applied. The distribution shows several highlighted peaks which can be interpreted. The peak around 3.7 kW corresponds to 16 A charging on one phase, the peak just above 5 kW corresponds to 25 A charging on a single phase, etc. The data records that fall within one of the highlighted peaks are labelled with the matching interpretation and this process is repeated for all combinations of conditions (single/double occupancy, Flexpower/reference stations and all current limitation levels - 8 histograms in total). The records that fall outside of the highlighted peaks cannot be interpreted and are not labelled. They are caused by unknown factors such as reduced charging power when the battery approaches a full state-of-charge.

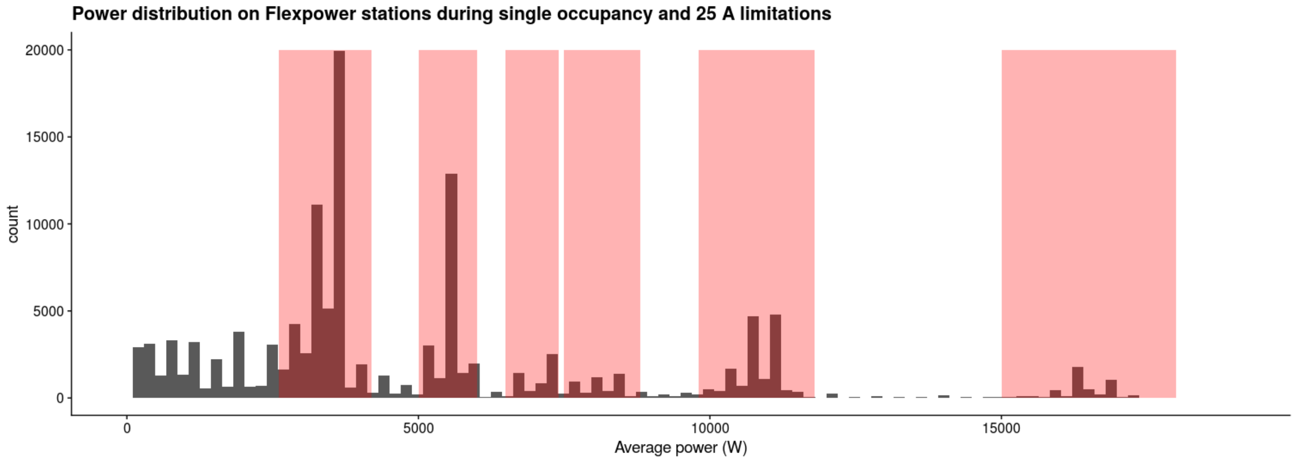

Figure 13: Histogram showing the average power for each interval in the meter values where charging took place on a Flexpower station during single occupancy and when the 25 A limitation was applied (day time under cloudy conditions).

After the interpretation process of the distributions, the labels are gathered for each unique RFID, generating a profile of the charging behaviour under various conditions. The final vehicle category is inferred from this profile. For example, an RFID with many 16 A single phase labels on reference stations, but 25 A and 32 A single phase labels on Flexpower stations will be classified as a 1x32 A - 7.4 kW vehicle, while a vehicle that has only 16 A single phase labels on both reference and Flexpower stations will be classified as a 1x16 A - 3.7 kW vehicle. The RFIDs which show inconsistent charging behaviour or have too little data to make a conclusive decision are classified as 'unknown'. A limitation of classifying RFIDs based on their charging characteristics is that 25 A or 32 A vehicles that have only charged on reference stations are indistinguishable from 16 A vehicles. This leads to an underrepresentation of the >16 A categories in the final classification.

Table 8: Examples of vehicles in the market for each of the categories.

Nominal powers	Configurations	Vehicles
3.7 kW	1 phase - 16 A	Toyota Prius Plug-in Hybrid
7.4 kW	1 phase - 32 A or 2 phases - 16 A	Jaguar I-pace Volkswagen e-Golf
11 kW	3 phases - 16 A	Tesla Model 3 Long Range RWD
17 kW	3 phases - 25 A or 3 phases - 32 A	Tesla Model S Standard Range Audi e-tron S 55 quattro

2.5.2. Results

The effectiveness of the detection algorithm is evaluated with Figure 14. On the horizontal axis, the maximum energy charged during a session (in kWh). On the vertical axis, the maximum power during the same session. Finally, the colour of the points corresponds to the category of the vehicle. The figure shows clear clusters of data points that have a strong correlation to the result of the classification. The reason that not all data points are located exactly in the matching clusters is that the maximum power is plotted which is an extreme value and not always represents the overall behaviour. There is also a small fraction of RFIDs that are not uniquely associated with a single vehicle (vehicle upgrade or company card), which can explain some of the deviations.

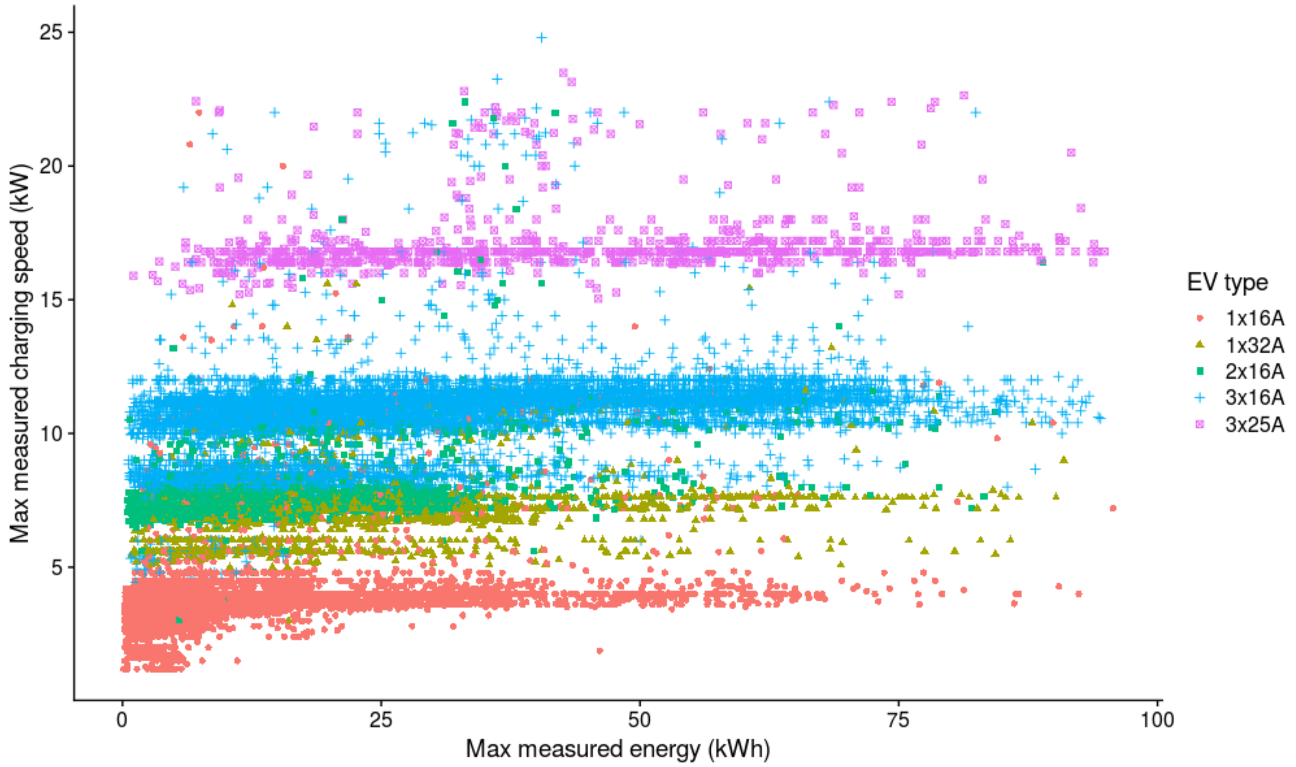

Figure 14: Plot showing the maximum power versus the maximum amount of energy charged in a single transaction for each RFID in the dataset.

Finally, Table 9 shows the distribution of the RFIDs in our dataset over the different categories. About half of the identified vehicles are single phase 16 A. It is consistent with Figure 1, as most of the PHEV are in this category and they represent about 50% of the current market in the Netherlands. Second largest share is the three phase 16 A, responsible for 27% of the RFIDs. This category includes the Tesla Model 3 , which has a market share of around 30% in the Netherlands. These two checks confirm that the vehicles categorisation is in the right range.

Table 9: Categorisation of vehicles during the Flexpower 2 pilot.

vehicle category	number of sessions	sessions (%)	number of RFIDs	RFIDs (%)	Energy (MWh)	Energy (%)
1x16 A	172347	53%	15393	48%	1323.73973	32%
1x32 A	36551	11%	1881	6%	522.02008	12%
2x16 A	20612	6%	2518	8%	280.14431	7%
3x16 A	75832	23%	9086	29%	1713.8374	41%
3x25 A	12898	4%	797	3%	290.2001	7%
Unknown	7760	2%	2093	7%	66.35886	2%
Total	326000	100%	31768	100%	4196.3	100%

2.6. Error detection

2.6.1. Principle of the error detection

During the pilot, the Flexpower stations were monitored by analysing the meter values and the applied current limitations. The results were discussed in a collaboration between the AUAS and Elaad, leading to a final list of approved stations consisting of 432 charging stations.

Each charging station is monitored individually. The three phases power computed from the charging profile vector is used as a base for the error detection and the meter values. The meter values timestamps are then rounded to the quarter of hour below, allowing the comparison with the profile power. To avoid false detection, the comparison is dismissed during the change of power (for example at 18:00, when switching from full to reduced power).

The error detection is made in two steps. First by looking at each socket individually and then by checking the sum of the powers of the two connectors.

If the power used by a connector or the sum of the connector is higher than authorised by the profile, the transaction will be marked as faulty. The same logic applies for a dual occupancy, but both transactions are stored.

To avoid the false detection during the profile transition (from high to low current or reverse), a charging session must have at least 4 faults detected to be stored. It is otherwise, not considered as faulty.

Due to the assumption of three phases vehicles to compute the power allowed by the profile, three cases are not detected because the power is lower than what is allowed whereas the current is higher.

Table 10: Cases undetected with this method

Cases		Limits	
Configuration	**Power**	**Current**	**Power**
1x16 A	3.6 kW	8 A	5.5 kW
1x32 A	7.4 kW	25 A	17.2 kW
2x32 A	14.7 kW	25 A	17.2 kW

This is clearly an issue as the single-phase vehicles limited to 16 A represent 48% of the vehicles and 53% of the transactions (see Table 9).

2.6.2. Results

The share of (i) charging stations and (ii) sessions found defective is relatively small with, on average, respectively 4% and 0.08%. Even by doubling these numbers to take the 16 A vehicles sessions in consideration, the number of faulty sessions would remain low at 0.16%. Two main causes are identified creating the faults:

- The Vattenfall back end was unable to connect to the charging station. The profile could not be transferred.
- The charging station refused the profile.

In both cases, the charging stations applies the 35 A limit for the entire day. Due to the very low percentage of erroneous sessions, these are not removed in the analysis further conducted.

Unfortunately, due to a lack of support from the charging station manufacturer, the dual occupancy fault causes are not identified.

There is however a need to improve the reliability of the vehicles category detection to accurately check the 16 A vehicle sessions as they represent about half of the charging sessions.

3. Results of the Flexpower operational pilot

3.1. Effect of Flexpower 2 on charging behaviour

3.1.1. Objective and methodology

One of the questions within this pilot is to what charging behaviour will change due to the different charging characteristics of the Flexpower stations as compared to regular (reference) stations. This analysis is intended to answer this question: do Flexpower charging stations lead to additional or more limited charging due to the available Flexpower capacity profile? The hypothesis is that due to the higher average power available during the day, EV users will be attracted to the Flexpower charging stations.

To answer this question and test the hypothesis, data from 432 Flexpower and 396 reference stations is analysed.

The analysis starts the 1st of December 2018 (see Figure 15 and Figure 16; the white background), 6 months before the kick-off of the Flexpower 2 pilot in order to compensate for any autonomous developments. On the 7th of May 2019, the official start date of the pilot, stickers were applied to the Flexpower charging stations (which in theory would create awareness for the altered charging opportunities at the Flexpower stations), but the profiles were not yet deployed (red background). Finally, on the 1st of November 2020, the profiles were applied (green background).

Two criteria are evaluated:

- The weekly percentage of sessions occurring on the reference and Flexpower stations
- The weekly percentage of energy charged on the reference and Flexpower stations

In a first step, the evaluation is conducted on the whole user population. Then it is focused on the taxis.

For all four cases, once the Flexpower's percentage is calculated (sessions and energy), the slope of the linear regression is computed. If the slope is positive, it means that the Flexpower ratio increases. Put differently, it means that a higher share of sessions or energy are counted on the Flexpower stations than on the reference stations. At the contrary, if it is negative, the reference stations ratio increases. Finally, if the slope is close or equal to zero, then there is no trend to extract from the study. The users are not avoiding for or attracted to using the Flexpower stations.

This method offers the advantage to eliminate the unbalance number between the two stations types as we are looking for the 1st derivative, eliminating the constant.

3.1.2. Results

Figure 15 shows two plots. On the left, the percentage of sessions on the Flexpower 2 stations is plotted; on the right the weekly ratio of the energy charged on the Flexpower stations regarding to the sum of the energy charged on both the reference and Flexpower stations.

The percentages of sessions (left), is computed by dividing the number of sessions counted on the Flexpower 2 stations by the total number of sessions on both the Flexpower and reference stations. Even if it fluctuates, the line is globally horizontal, with a slope of 0.21% per year.

On the right of the same figure, the weekly ratio of the energy charged on the Flexpower stations compared to the sum of the energy charged on both the reference and Flexpower stations. Here again the line is globally horizontal with a slight negative slope (-0.82% per year). It is not significant to conclude a trend of less energy charged on the Flexpower stations.

It can thus be concluded there is no clear avoidance or search for Flexpower stations by EV users.

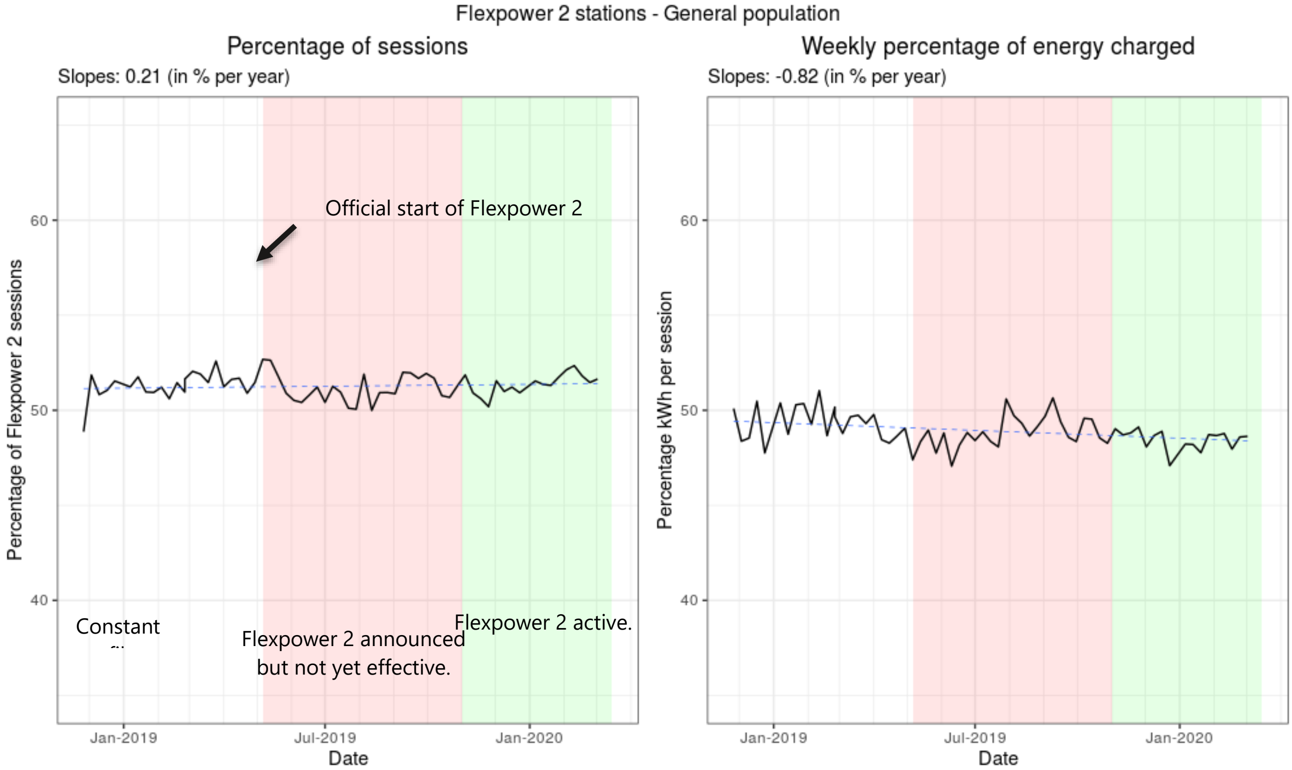

Figure 15: For the general population, weekly percentage ratios of sessions (left) and percentage of energy charged (right) on Flexpower 2 stations. The slopes are close to 0% per year and looks constant through the three considered periods.

After the evaluation of the general population, the study focused on the taxis. These professional users are generally more aware of the good places to charge. If there is an issue with the Flexpower stations, it will be noted by them. The same method applied in Figure 15 was applied to obtain Figure 16, which is limited to the taxi population. Here again no specific trend is visible. The taxis are not avoiding or looking for the Flexpower stations.

One notable point, however, is the number of charging sessions (Figure 16, left). The ratio is always above 50%, meaning that a significant amount of charging sessions occurs on the Flexpower 2 stations for the taxis. This trend was already before the start of the operational pilot. It can thus not be concluded that taxi drivers tend to adopt or prefer Flexpower 2 stations as these charging stations already had a high utilization rate by taxis prior to the Flexpower2 pilot.

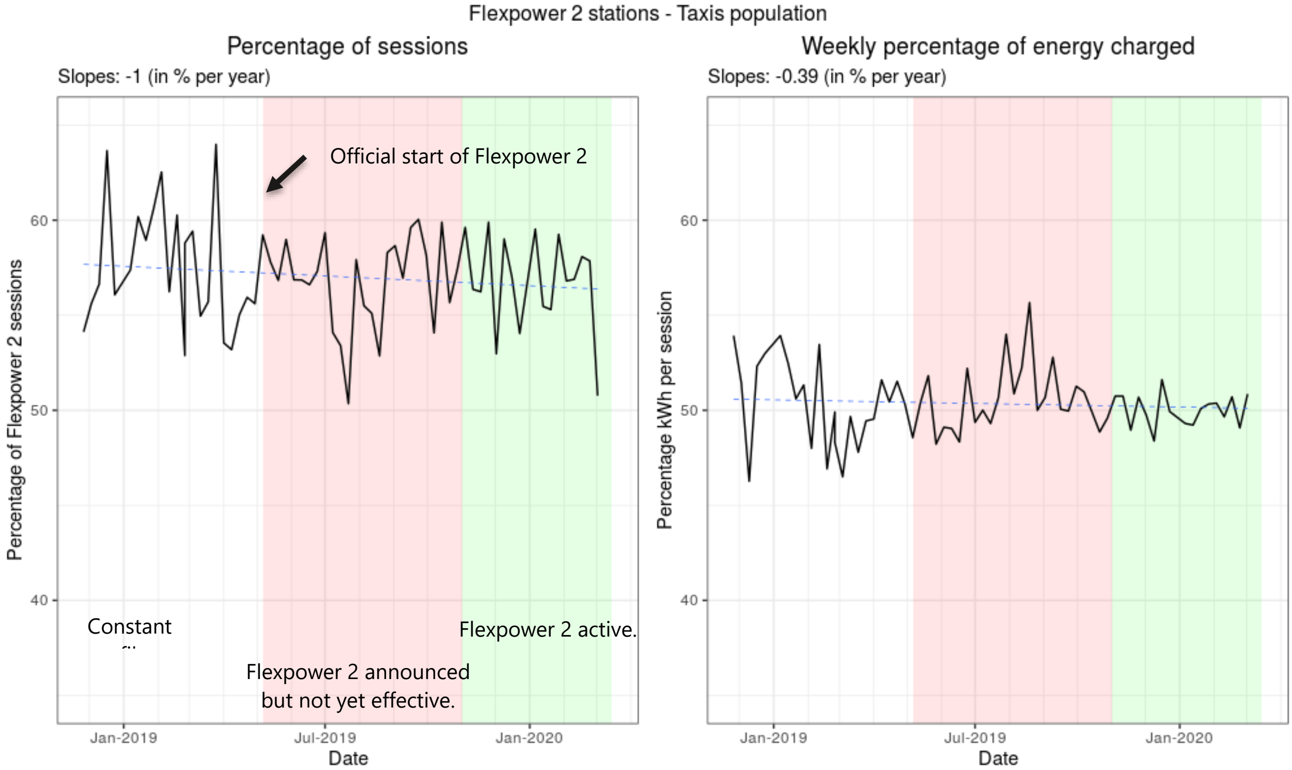

Figure 16: Ratio of the energy charged in the Flexpower stations regarding to the reference for the general population. The slope is constant and slightly negative.

3.1.3. Conclusion

For both the general EV users as well as the taxi drivers no significant shifts in sessions or energy is visible. And thus, the data indicate that EV-users are not avoiding or searching the Flexpower 2 charging stations. As such the Flexpower 2 stations did not lead to a change in charging behaviour (in terms of preferential charging stations). This may not be that surprising as EV drivers have not been actively approached and informed with the Flexpower pilot.

3.2. Flexpower impact for each EV categories

The previous chapter shows that there is no real trend for the users to avoid or search for the Flexpower charging stations.

In this chapter, the charging power on reference and Flexpower stations is investigated. To conduct this analysis, a charge duration curve is plotted [13] for each of the identified vehicle categories (see Table 4). A load duration curve is the plot of load versus time duration for which that load was persisting. It is built by plotting the average power per measured interval ranked in descending order and normalised to percentiles. Because of this normalisation, vehicle categories with different amounts of sessions can be compared.

Figure 17 shows the load duration curve for the 3 EV categories identified (16, 25 And 32 A) for both the reference (dashed line) and the Flexpower charging stations (solid line).

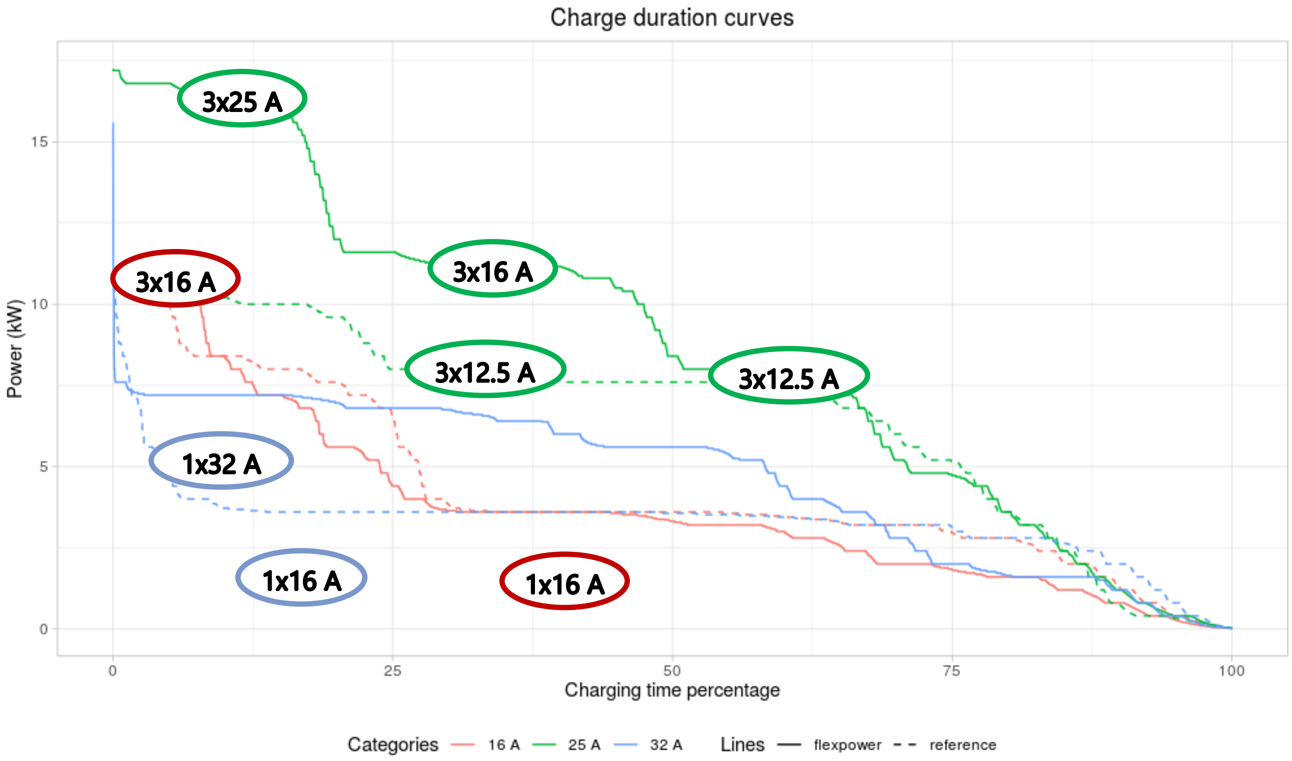

Figure 17: Examples of charge durations curves for the 16, 25 And 32 A vehicles categories for both the reference and Flexpower stations. The number of phases and charging current corresponding to the plateaus in the figure are circled.

There is no significant difference between the reference and Flexpower lines for the 16 A vehicles. On the left, where the power is at its highest level, both red lines are close to each other. The only noteworthy feature is that the Flexpower has a higher number of sessions charging at around 8 kW.

That's a different for the 25 And 32 A vehicles. Whereas the green and blue dashed lines (reference) are close to the red ones, the solid lines green and blue are at the top of the Y axis, where the power is high. This plot clearly shows the advantage the high current vehicles can take from the Flexpower stations. This advantage remains almost until 50% of the time.

On the right of the plot, all the lines converge to the 0 kW when the batteries are full.

Figure 17 shows the advantage each category of vehicle can take from the Flexpower stations. The higher the current capabilities, the bigger the benefit.

3.3. Average charging power per session

To investigate the impact on the effective charging power of the different vehicle categories, we calculate the average power on the Flexpower and reference stations as a function of time of day. Since the time-dependent profile is the same on all Flexpower stations since the 1st of November 2019, the results for all stations can be aggregated. The results are presented in Figure 18. The blue line is calculated from sessions on reference stations, which always have a limit of 25 A for both sockets combined and have 16 A fuses on the individual sockets. It is interesting to note that the reference stations offer the same condition all day but nevertheless the charging power fluctuates over time, especially for the categories charging on more than one phase, and is significantly lower than the theoretically expected value (3.7 kW for 1x16 A, 11 kW for 3x16 A). This shows that there are other factors besides the charging station characteristics that determine the effective power. The red line shows the average power on Flexpower stations that have a time-dependent current limit. All categories show a reduction of 30-50% in power during the evening hours (18:00–21:00) because of the lower current limit. The rest of the dynamics differ between the vehicle categories.

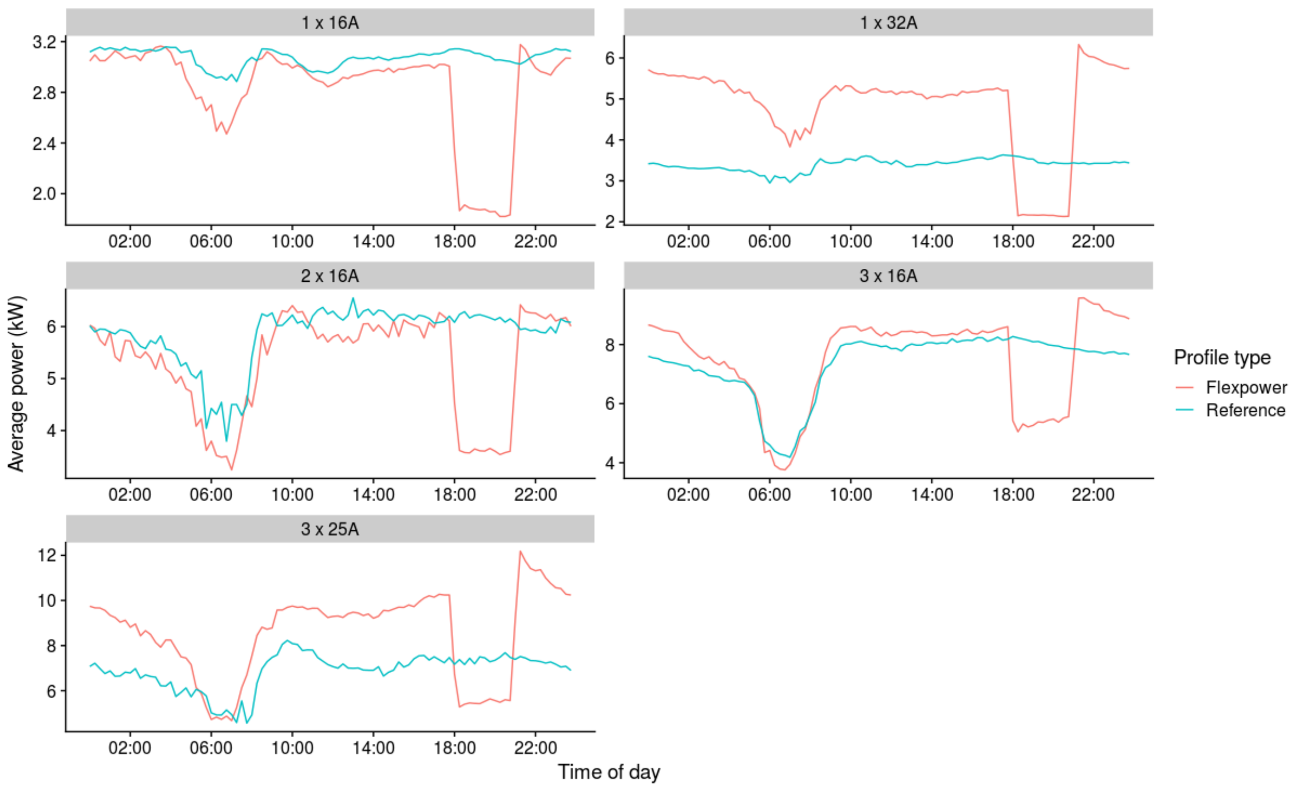

Figure 18: The average power over the day for the different vehicle categories during charging. The resolution of the graph is 15 minutes, which is limited by the resolution of the data.

The 1x16 A and 2x16 A categories are internally limited to 16 A and therefore cannot profit from the increased current limit during off-peak hours. The same applies for the 3x16 A category, even though this category shows an increase in power after the evening hours. This can be explained by a double occupancy effect. Public charging stations in Amsterdam have two sockets, but the current limit applies to the whole station. The station uses software to optimize the energy transfer to both sockets and can provide full current to both sockets if the total number of connected phases is not higher than three. A 3x16 A vehicle which is connected simultaneously with another vehicle always exceeds this limit and the current is shared between the sockets. On regular charging stations there is 25 A to share and this configuration results in charging at 12.5 A per socket. On Flexpower stations the vehicle can continue to charge at 16 A even during double occupancy because the station-wide limit is increased to 35 A. This effect is strongest in the evening when the occupancy rate is highest. The double occupancy effect can also occur for 1x16 A vehicles but because of the high market share of single-phase vehicles the criterion of >3 phases is not exceeded very often.

The 1x32 A and 3x25 A categories can profit from higher current levels during off-peak hours and the removal of the 16 A fuse on the sockets.

The dip in power in the early morning is the result of a very low number of active charging sessions that are all approaching a full state-of-charge. The last part of the charging process is often slower due to the battery management system which reduces the average power.

3.4. Total grid load of EV charging

The results in Figure 18 do not reflect the number of active charging sessions, which varies a lot during the day. When we average the charging power over the number of stations instead of the number of active sessions, we get a better picture of the total grid load contribution of EV charging over the day (an idle charging station is still counted in the average). These results are presented in Figure 19.

The blue line represents the average power of a reference station and clearly shows that the peak in demand occurs between 18:00 and 22:00. The energy transfer then continues to decrease until 07:00. The average power per station is approximately constant during the day.

The red line representing the average power of a Flexpower station follows the same trend, except for the artificial decrease in power between 18:00 – 21:00 because of current limitations. This creates outstanding demand which is met at an accelerated rate after limitations are lifted, creating a rebound peak. Even though this rebound peak is higher than the original demand peak, it occurs at a time when household demand has already decreased causing the total load on the grid to be more evenly distributed. Flexpower reduces the load on the grid during the peak (at 19:30) with on average 1.2 kW per station. Due to an initial wrong configuration of the meter value sample interval in the Flexpower stations, the meter values where not always transferred between 18:00 – 21:00. This means the grid load of Flexpower stations is slightly underestimated during this time window because stations that are charging appear to be idle. We estimate this effect to occur at approximately 10% of the transactions, leading to a corrected estimated avoided grid load of ~1.1 kW.

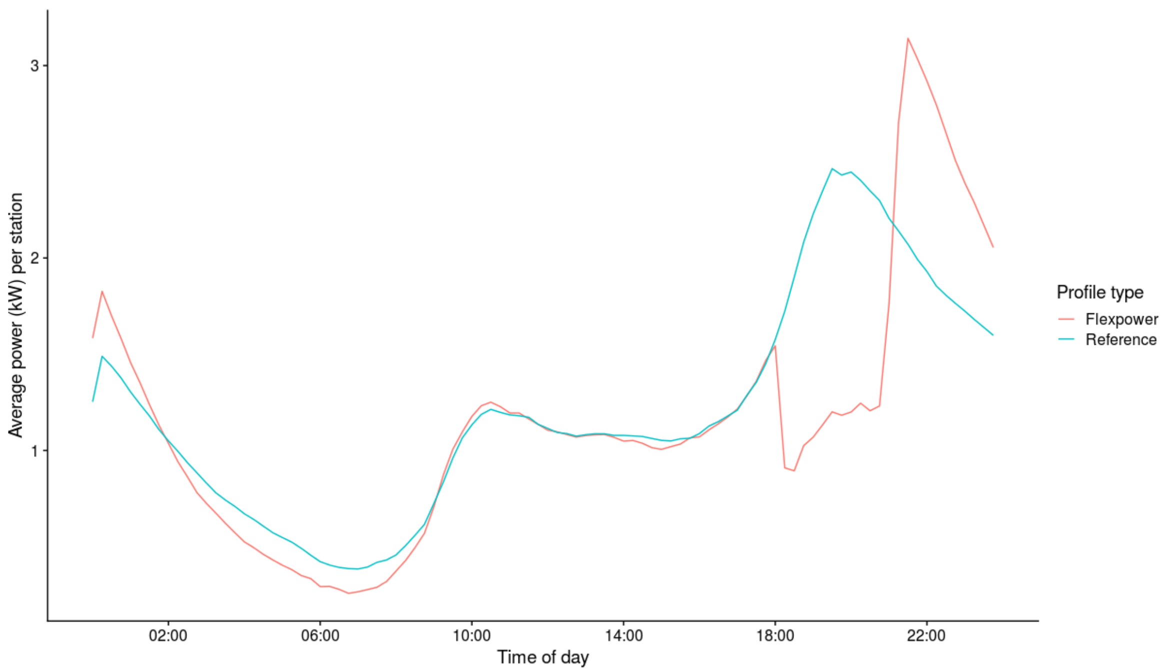

Figure 19: The average power per station over the day for Flexpower and reference stations. The plotted value represents the total grid load contribution of EV charging.

3.5. Impact on the user

An important indicator for smart charging in practice is the extent to which EV users are positively or negatively affected by providing a Flexpower profile compared to the current standard static charging profile. A session on a Flexpower station is defined as being negatively affected when it results in a lower amount of charged energy compared to a similar transaction on a reference station. However, since the amount of charged energy in a session depends on the battery size of the EV and the state-of-charge (SOC) of the batteries we prefer to analyse this indicator by looking at the average power per transaction. The average power is directly proportional to the amount of energy charged and is insensitive to effects of large batteries and SOC.

Figure 20 shows the distributions of the average power per transaction for the five different vehicle categories. We can identify several shifts in the distributions that correspond to the positive and negative impact of the Flexpower profile. For the 1x16 A category there is a shift from 3.7 kW to 1.9 kW, which is the result of the current being reduced by a factor of two during evening hours. The 1x32 A category also shows the shift to lower power but it is much smaller, but also a much larger shift to values above 4 kW. This is the result of being able to charge at 25 A and 35 A during off-peak hours. The 3x16 A category shows a shift to lower power levels because of current limitations but also a positive shift from 8 kW to 11 kW. This can be explained by the fact that vehicles no longer have to share the current during double occupancy. The 3x25 A category distribution hardly contains the shift to lower power levels because the missed-out energy could be compensated during off-peak hours (the same process applies to the 1x32 A category). The double occupancy effect is also visible as well as the positive shift because vehicles can charge at 25 A during off-peak hours.

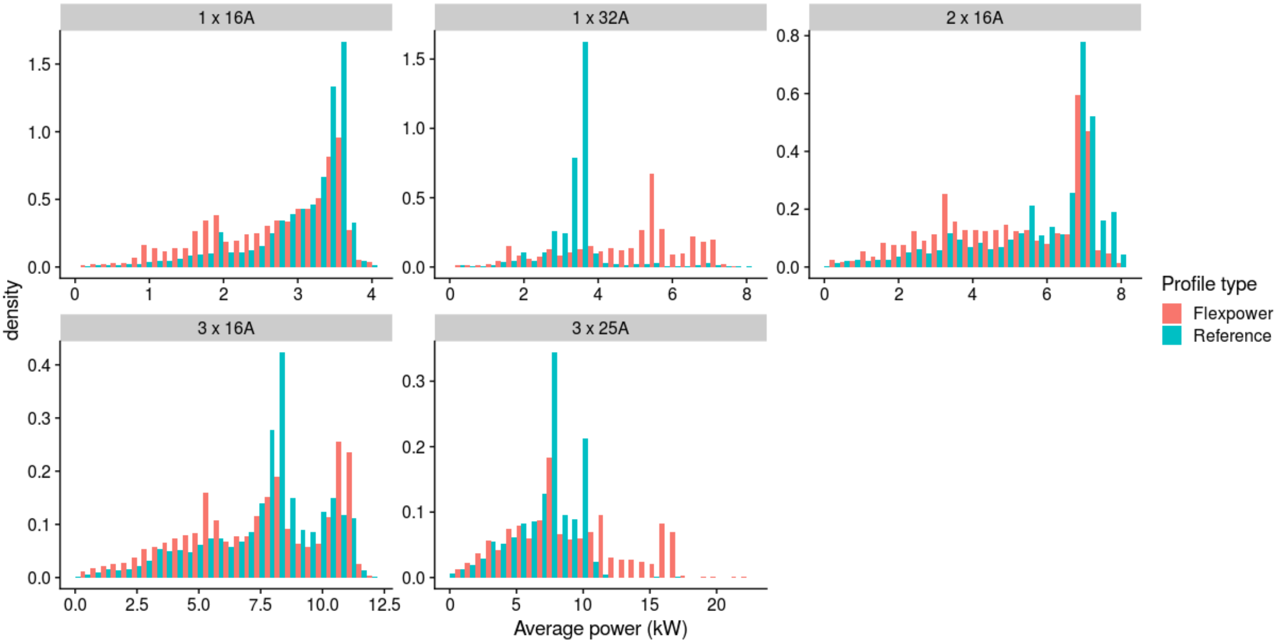

Figure 20: Distribution of the average power per transaction per vehicle category for Flexpower and reference stations. The average is calculated for the whole session, so periods of slower charging during the current limitation can be compensated in the preceding or following hours. Only sessions that have not finished charging upon disconnection are shown (37.9%).

The number of positively and negatively affected sessions are quantified as the percentage of transactions associated with these shifts and are determined by subtracting the two distributions from each other. This leads to the results in Table 11. The numbers show that the 1x16 A and 2x16 A categories have almost no advantage of Flexpower and the 3x16 A has only limited benefit (which is in line with the results in Figure 18). The 1x32 A category has the largest advantage, followed by the 3x25 A category. The lower negative impact percentages of both these categories show that a small negative impact is often compensated during more favourable conditions beforehand or afterwards.

Since most sessions complete charging before being disconnected, the total share of negatively affected sessions is only 6%. Most of these affected sessions are PHEVs which will not experience any range anxiety because of Flexpower. The vehicles capable of charging over 3 phases or at higher current are less negatively affected and often even positively affected by Flexpower (the total share of positively affected sessions is 4%). Overall, we can conclude that the impact of Flexpower on customers is very limited and that the positive and negative effects are of equal magnitude.

Table 11: Percentage of charging sessions that was influenced by Flexpower and how. The numbers only reflect the sessions that were not completed at the moment of disconnection.

Vehicle category	Negative	No impact	Positive	Sessions that have completed charging
1x16 A	19%	77%	4%	64.7%
2x16 A	23%	77%	0%	62.6%
1x32 A	5%	28%	67%	59.8%
3x16 A	15%	74%	11%	58.5%
3x25 A	2%	64%	34%	52.9%

3.6. *Impact on sustainable energy overlap*

The time-dependent capacity profile on Flexpower stations is updated each night depending on the weather forecast for the coming day. If the probability that the sun will shine (parameter **d1zon** from the Dutch 'weerlive'

API [14]) is 40% or higher, the current limit is set to 35 A between 06:30 and 18:00, if it is lower it is set to 25 A during this time. This dynamic adaptation of the smart charging profile is done to investigate to what extent EVs can be used to absorb peaks in local solar power generation.

Figure 21 shows the average power per session and the average power per station for both solar intensity levels. It can be seen that the higher current limit leads to slightly higher power per session and also to a slightly higher power per station, indicating more energy was charged during the day and relieving a small portion of the evening load. The difference is not very large because only a limited share of vehicles can profit from the increased current limit during high solar intensity conditions and double occupancy, for which the higher current limit gives an advantage, occurs less frequently during the day. Also, if vehicles complete charging before disconnecting, a higher power will not lead to higher energy volume, the battery will just be fully charged faster. If EVs are to be used to absorb future peaks in local solar power, extra incentives are needed to promote charging during overlapping hours.

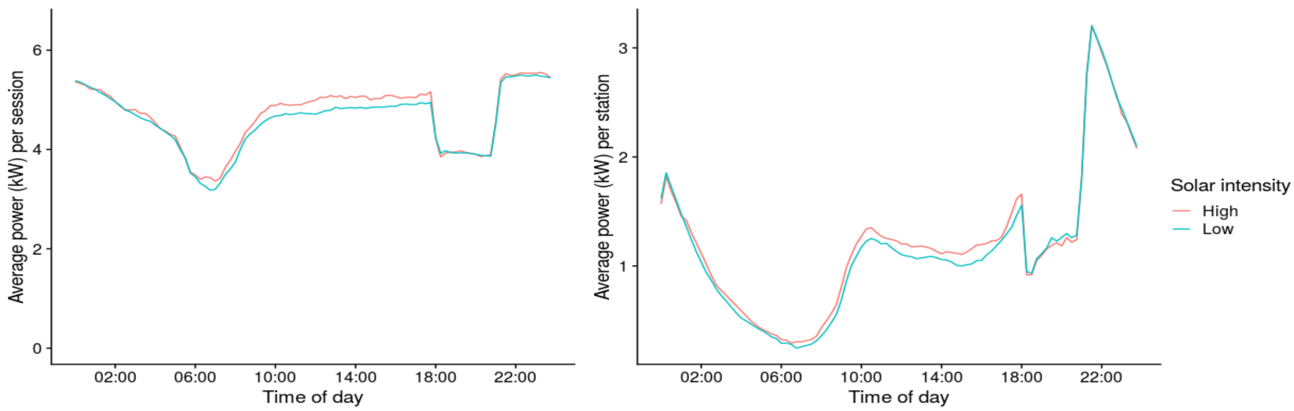

Figure 21: The average power per active session and per station over the day for different weather conditions.

3.7. Simulation model

The possibility to apply a time-dependent current limit on live charging stations with real users is a unique opportunity to evaluate smart charging strategies under real-world conditions. However, because there are so many known and unknown factors that influence the charging process and often only one or two transactions take place on a charging station per day, it takes many stations and several weeks to be able to draw reliable conclusions. Also, it is undesirable to subject real users to more aggressive profiles, limiting their access to energy and directly impacting their mobility. Therefore, it is of great added value to be able to simulate the impact of smart charging profiles.

To ensure the simulation gives reliable results, we use empirical measurements of actual charging sessions as input for the model, as it is known that these are very different from theoretical values. The occupancy of a station, the vehicle category and the applied current limit are known factors that influence the charging power. We construct a power table containing every combination of these factors and determine the average charging power under these circumstances from the data. Figure 22 shows an example of these average power values taken from the data for 3x16 A vehicles for all combinations of occupancy and current limit. The double occupancy line shows that an increase in current limit is always beneficial since these 3-phase vehicles have to share the current with the second socket. They will reach their full potential of 16 A only when 32 A is available for the whole station. For single occupancy, the vehicle already reaches its maximum power at a current limit of 16 A and the power level remains stable after this.

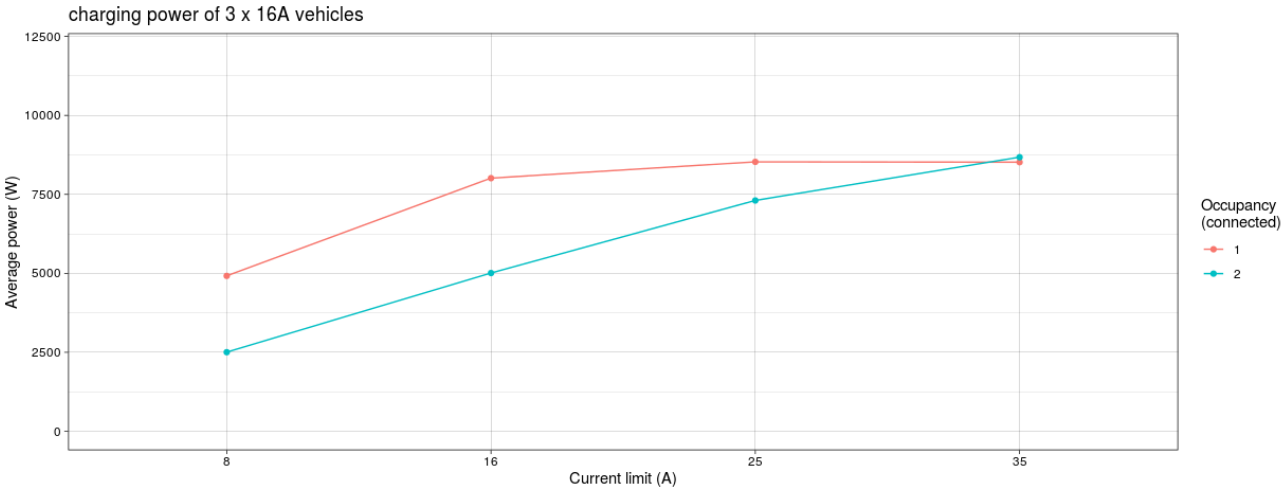

Figure 22: The average charging power taken from the data for vehicles classified 3x16 A under a range of circumstances.

The simulation takes a real transaction and simulates what this session would have looked like if a time-dependent capacity profile had been implemented. For each 15-minute interval a value is taken from the power table corresponding to the conditions as they were at that moment in time. A distinction is made between sessions that completed charging before being unplugged and sessions that continued charging until the connection was ended by the user. When simulating the first scenario, the process stops when the total energy volume reaches the amount that was charged in the original transaction, as the battery capacity is the limiting factor in this case. The amount of time it takes to reach this energy volume will be shorter or longer depending on the conditions during the transaction. When simulating a non-completed transaction, the charging process continues until the end of the transaction is reached. This can result in a larger or smaller amount of energy depending on the conditions during the session. Two examples are shown in Figure 23. The left example is of a transaction that stops charging before disconnection and is therefore assumed to have reached a full state of charge. The simulation model stops charging when reaching the same amount of total energy but takes a longer time to reach this amount. The right example continues charging until disconnection and is therefore assumed not to have reached a full state of charge. The simulation model also continues to charge during the full connection time and charges a larger amount of energy than the original transaction.

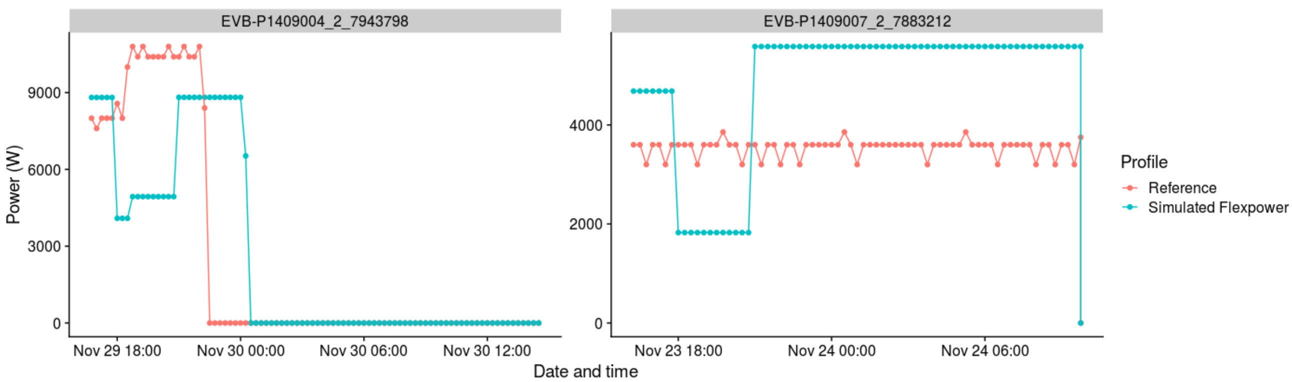

Figure 23: Two examples of the charging power over time during a transaction on reference station and the results of the simulation model on that same transaction.

3.7.1. Validation of simulation model

To validate the reliability of the simulation model, the transactions from a random selection of 50% of all stations (reference and Flexpower) were simulated with the corresponding capacity profile and the results were compared to the actual measurements on the remaining 50% of the stations. In total, over 150.000 transactions were run through the simulation. The aggregated results are shown in Figure 24.

It can be seen that the grid impact can be accurately simulated with our model.

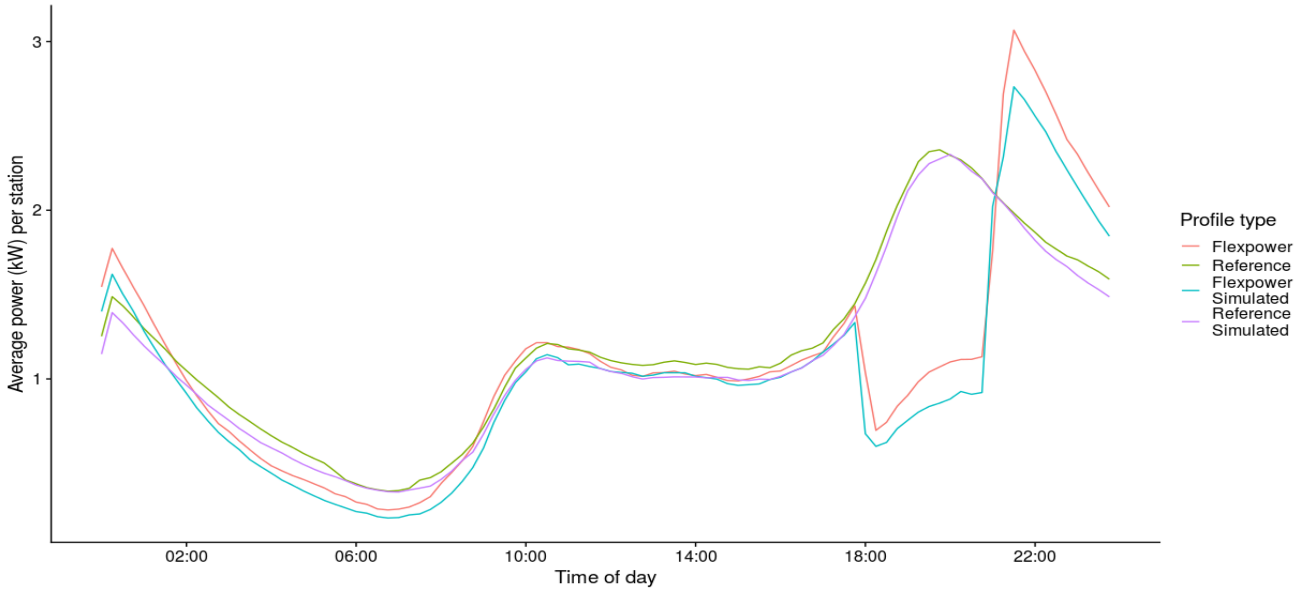

Figure 24: The average power per station (grid impact) for real transactions and simulated transactions.

Because it was shown that the simulations give reliable results for the grid impact, we can now simulate different scenarios for a fixed set of transactions. Since the input transactions are now the same every time, an accurate comparison can be made of the grid impact depending on the specific profile configurations, but also of how individual transactions were influenced by the profile in terms of total energy or charging time.

3.7.2. Flexpower with different current limits during evening hours

The first set of scenarios was chosen to investigate how the current limit level during the evening hours influences the avoided grid load and the rebound peak. Simulations were run where the current limit level between 18:00 – 21:00 was set to 8 A (actual Flexpower profile), 12 A, 16 A, 20A, 25 A and 35 A. The results are shown in Figure 25. Since we do not have actual measurements of charging behaviour at 12 A and 20A, the power values were interpolated between 8 A and 16 A and between 16 A and 25 A since it is expected that the power in those intervals increases linearly with the current limit.

The lower the current limit during evening hours, the higher the rebound peak is, where the current limit of 35 A is the only line which does not show a discontinuity at 21:00, indicating there is outstanding demand at this time regardless of the conditions during the evening hours and there are conditions for which a 35 A limit is advantageous (e.g. double occupancy of 3-phase vehicles). The difference in grid load and magnitude of the rebound peak between the 8 A and 16 A current limits is much larger than the difference between 16 A and 25 A. This can be explained by the fact that all vehicles can profit from the increase from 8 A to 16 A, but only a limit number of vehicles can benefit from a higher current than 16 A.

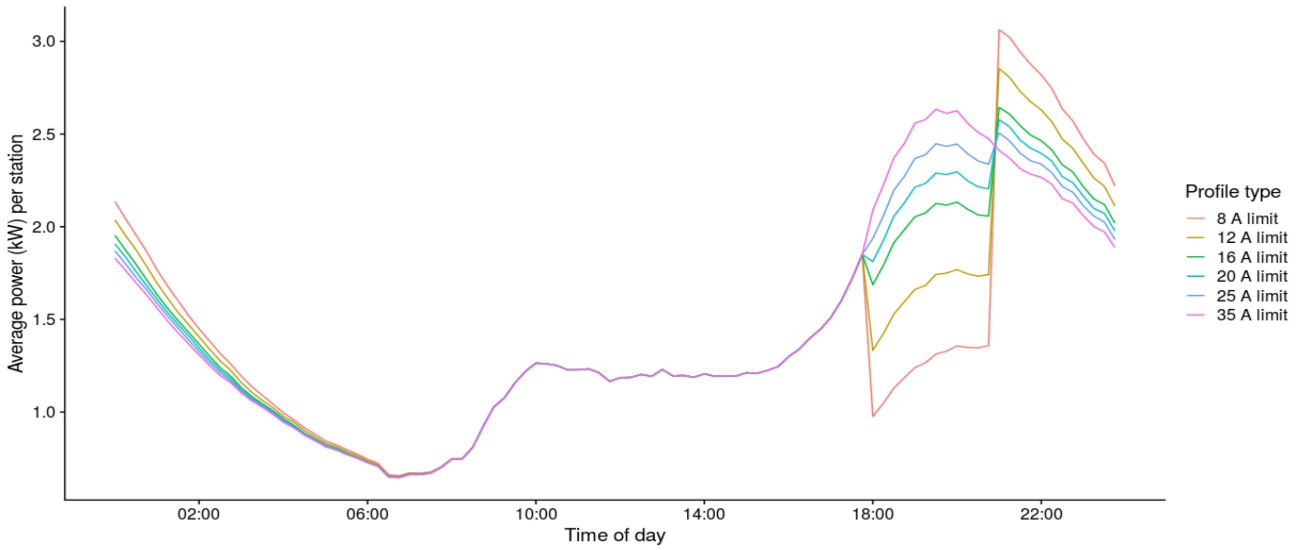

Figure 25: Simulation of a fixed set of transaction on capacity profiles with different limits during evening hours.

3.7.3. Flexpower on 3x25 A connections

The second scenario we have simulated is what would happen if we ran Flexpower on a non-upgraded grid connection, meaning that a 3x25 A connection is used in combination with a flexible capacity profile instead of the upgraded 3x35 A connections currently in place (which have much higher recurring costs). The results are shown in Figure 26. It can be seen that the availability of a current limit of 35 A only has some influence after limitations are lifted in the evening.

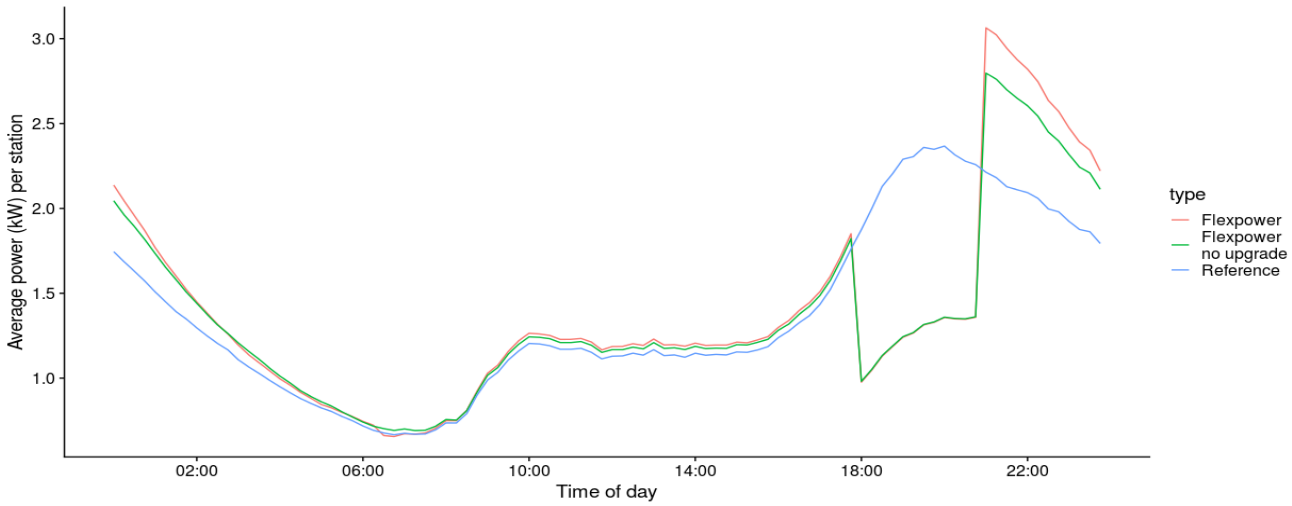

Figure 26: Simulation of a fixed set of transaction on the Flexpower profile on 3x25 A and 3x35 A connections compared to the Reference profile.

We can also look at the effect of the profile on the amount of energy that is charged in each individual session and calculate the amount of positively (more than 110% amount of charged energy) and negatively (less than 90% amount of charged energy) affected sessions. The results for the Flexpower profile can directly be compared to the numbers in paragraph 3.5. The results for the 'Flexpower no upgrade' reflect what the impact would have been when running Flexpower on 3x25 A connections, so without the extra current availability, but with the time-dependent capacity profile and software driven current distribution and removal of the individual 16 A fuses on the sockets.

Table 12: Percentage of simulated charging sessions that was influenced by Flexpower on a 3x35 A connection. Negative means amount of charged energy is reduced by more than 10% and positive means the amount is increased by more than 10%. The numbers only reflect the sessions that were not completed at the moment of disconnection.

Vehicle category	Negative	No impact	Positive	Sessions that have completed charging
1x16 A	26%	74%	0%	64.9%
2x16 A	30%	70%	0%	67.4%
1x32 A	13%	5%	82%	57.8%
3x16 A	24%	60%	16%	56.7%
3x25 A	15%	25%	60%	53.4%

These numbers are a bit more extreme than the empirical numbers from paragraph 3.5, which can be explained from the fact that in the simulation model a comparison can be made on an individual session level while in the actual experiment we have interpreted shifts in the power distribution of a large group of sessions, which can obscure some smaller scale effects. The results do show a similar picture, namely that the 1x16 A and 2x16 A categories have no advantage but a disadvantage in the order of several tens of percent. The 1x32 A and 3x25 A categories have a large advantage and a lower disadvantage rate. The 3x16 A is in between, having a slightly lower disadvantage rate and some advantages due to Flexpower.

The numbers for the affected session for running Flexpower on 3x25 A connections are mostly similar and have slightly higher negative influence rates. The big difference is that the advantage for 3x16 A categories has disappeared because these vehicles can no longer charge at 16 A during double occupancy which was their only mechanism for achieving higher power. This effect also applies to the 3x25 A category which has a lower advantage as well.

Table 13: Percentage of simulated charging sessions that was influenced by Flexpower on a 3x25 A connection and how. Negative means amount of charged energy is reduced by more than 10% and positive means the amount is increased by more than 10%. The numbers only reflect the sessions that were not completed at the moment of disconnection.

Vehicle category	Negative	No impact	Positive	Sessions that have completed charging
1x16 A	30%	70%	0%	64.9%
2x16 A	30%	70%	0%	67.4%
1x32 A	14%	5%	81%	57.8%
3x16 A	25%	75%	0%	56.7%
3x25 A	17%	40%	43%	53.4%

3.7.4. Flexpower for a future fleet composition

Currently the EV market is dominated by PHEVs with small batteries and low charging power (they are classified in the 1x16 A category). The fleet composition is shifting towards more full electric vehicles with faster charging capabilities as technology continues to improve and governmental tax incentives have become available only for zero-emission vehicles. To investigate the impact on the grid by a change in vehicle composition, we have run the simulation on an altered version of the fixed set of transaction where 50% of the 1x16 A vehicles have been replaced by 3x16 A vehicles which are also assigned a larger battery size sampled from the actual population of 3x16 A vehicles. The results are shown in Figure 27. We can see that the load on the grid per charging station increases for both stations running Flexpower profiles as well as reference stations, but the increase is larger for the reference stations. The avoided grid load (difference between reference and Flexpower lines at 19:30, which correspond to the moment of maximum total load) increases from 1.05 kW to 1.16 kW.

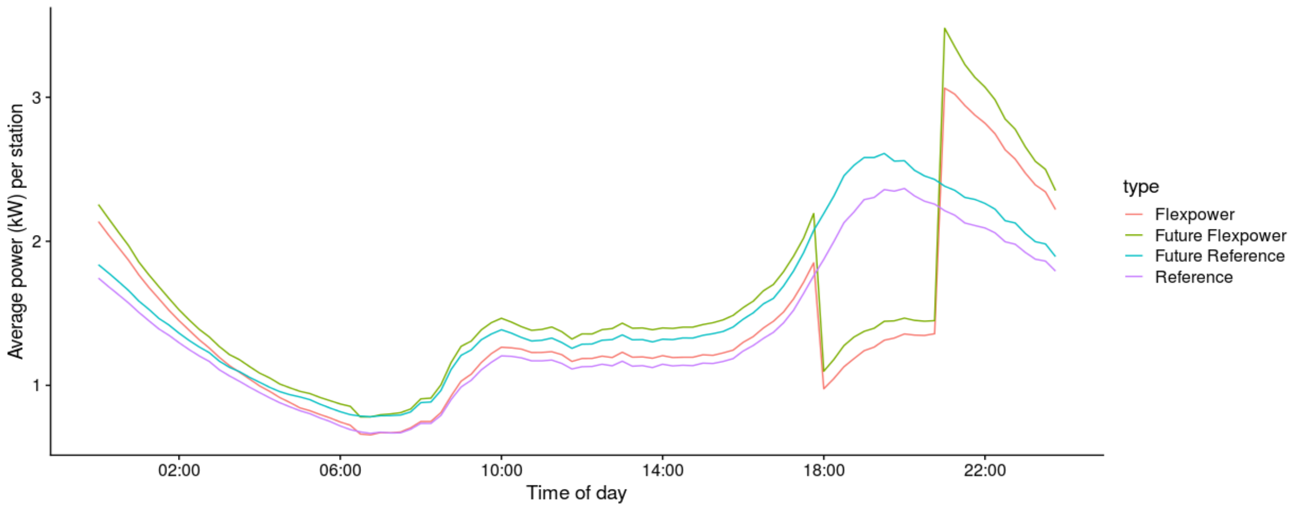

Figure 27: Simulation of the grid impact for a future fleet composition compared to the current situation.

The results from the simulation model show that the of time-dependent smart charging strategies can be studied in a virtual environment. Any set of real or hypothetical transactions can be evaluated on multiple profiles to evaluate the impact on the users, total sales, the grid load and overlap with generation of sustainable energy. This allows us to estimate the business case of new strategies without directly exposing real users and without weeks of delay to accumulate sufficient data.

4. SEEV4-City Results – Key Performance Indicators (KPIs)

4.1. Methodology (summary)

Within the SEEV4City project three KPIs have been used to monitor progress: (A) CO_2 reduction, (B) energy autonomy and (C) avoided grid investments. The methodology for calculating their contributions is described in more detail in the project's KPI Methodology and Methodology Report. For the Flexpower project the focus was on reducing grid impact (indicator C); and to a lesser extent on CO_2 emission reduction (indicator A). Energy autonomy was hard to establish given that applying smart charging on large scale was chosen over bidirectional charging in the Operational Pilot of Amsterdam. As such studying the effects on grid impact (and CO_2 emissions) became priority in the analysis (over energy autonomy).

4.2. Baseline and Final measurements: CO_2 reduction

4.2.1. Component data requirements

To compute the CO_2 emission reduction linked with the Flexpower smart charging, the following method is used:

- For each 15 minutes interval, the sum of the powers delivered by the reference charging station is computed.
- The sum is also computed for the Flexpower stations.
- From the ENTSO-E data available, the CO_2 intensity is computed based on the energy mix in the Netherlands. The CO_2 intensity is computed for each 15 minutes interval.
- Finally, for each charging stations types, the CO_2 emissions are computed for every 15 minutes and the emission in kg per kWh are computed.

4.2.2. Baseline and Final measurements

The capacity profile applied in the Flexpower pilot was designed to reduce grid impact, and (to a lesser extent) provide a better match between charging demand and solar generation by increasing current limits during more sunny days.

Results, in Table 14, shows that CO_2 emission reduction as a result of applying the Flexpower smart charging profile has been negligible, both during the Flexpower 1 and Flexpower 2 pilot. The applied Flexpower profiles do not lead to major shifts in charging volumes from mornings to (sunnier and generally less CO_2 emission intensive) afternoons.

By adding a current limitation in the morning during (expected) sunny days, it may be possible to provide a larger shift in charging volumes to the afternoon by EV drivers that start charging early morning (and stay connected until late afternoon). That could potentially increase the charge volume at hours with relatively low CO_2 emission intensity. Nevertheless, the majority of charging sessions takes place in evening times; and the weight of shifting actual charging times to more favourable (renewable) times of day will likely remain a small factor to achieve lower CO_2 emissions. More dynamic steering to renewable energy (both solar and wind) is then required. It is recommended to explore the potential increase of these scenarios in simulations.

Table 14: Effect of Flexpower on CO_2 emissions

		(i) Initial stage	(ii) End of Project	
		Value	**Value**	**Compared to (i)**
A. CO_2 Reduction				
A.1	Pilot CO_2 footprint - Flexpower 1 - Flexpower 2	461.94 kg/MWh 477.16 kg/MWh	461.53 kg/MWh 476.83 kg/MWh	-0.09% -0.07%

4.3. Baseline and Final measurements: Grid investments

A major driver for Flexpower was to establish lower charging during evening times and thereby avoiding peak loads on the grid. Figure 28 shows the results of the average power profiles of reference stations versus Flexpower stations, indicating that indeed the peak load during peak hours was reduced significantly. In chapter 4 an average load reduction of around 1.1 kW per charging stations was found. Multiplied by the amount of charging stations in this study (432), this adds up to around 470 kW during peak times for the city of Amsterdam. Although still a small percentage of the total load during evening times, the sheer size of the number of chargers still accumulates to significant volumes.

Applying the indicator for global grid investments per kW (€100/ kW) applying Flexpower on the scale in the Flexpower2 pilot may lead to deferred grid investment costs of €47,000. Applying a profile such as Flexpower on larger scale may accumulate to much higher savings. Not only can smart charging during peak hours be applied to public and semi-public charging stations (in the Netherlands alone more than a factor 100 higher than the current number of 432 Flexpower stations), but also to private charging stations (currently more than 100,000 in the Netherlands). The potential for reducing charging demand by smart charging practices like Flexpower runs in the megawatts scale; while deferred investments costs can run on tens of millions of euros.

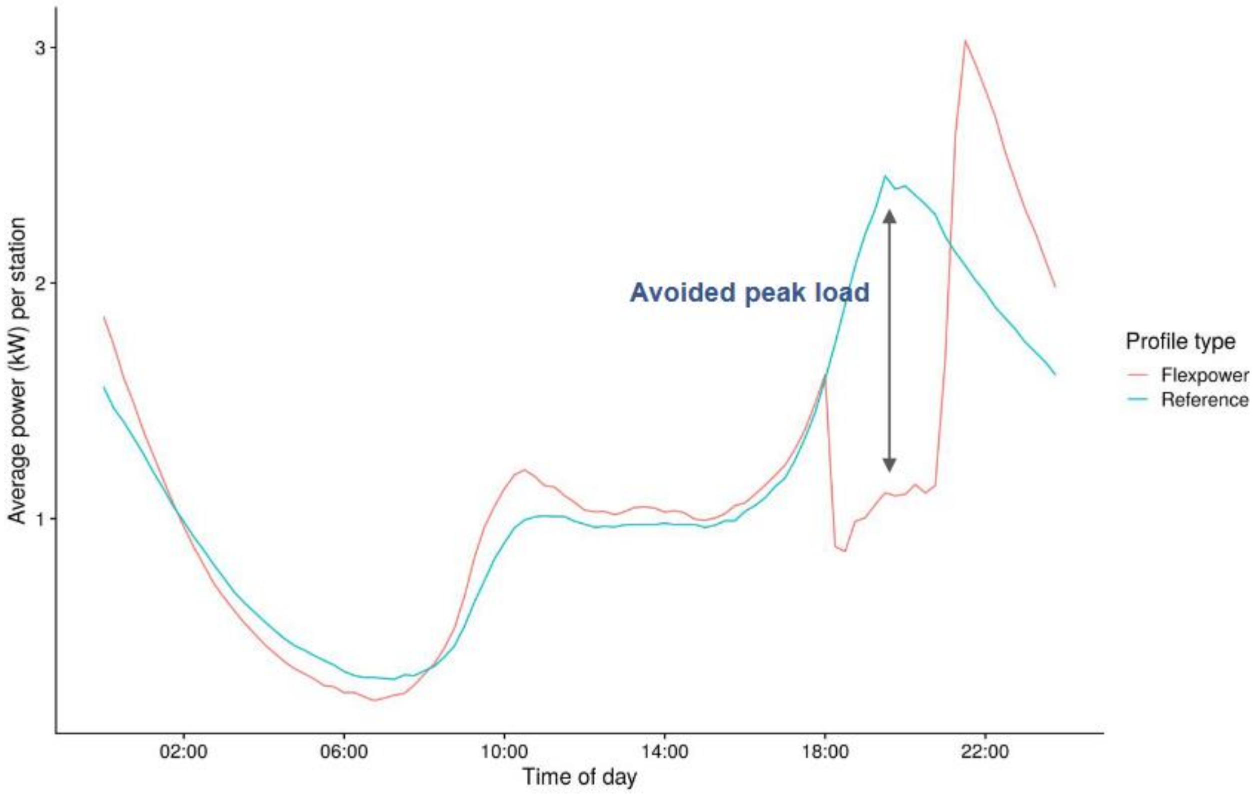

Figure 28: Power peak avoided due to the Flexpower profiles

Table 15: Grid investments

		(i) Initial stage	(ii) End of Project	
		Value	**Value**	**Compared to (i)**
C. Grid Investment Deferral				
C.1	Peak Demand Value	2,3 kW	1,2 kW	1,1 kW

5. Cost-Benefit Analysis

For the cost-benefit analysis it is useful to compare the current public charging stations (3x25 A grid connection) with the Flexpower charging stations (3x35 A grid connection). We assembled the structural cost and benefit factors that should be factored in when applying Flexpower profiles (both Flexpower1 and 2 assembled) in other contexts. Pilot-related (research and development) costs are mentioned but not considered in the overall cost benefit analysis.

Costs and benefits will vary for different stakeholders, e.g. the CPO, the grid operator, the municipality and the user. For this analysis we take a CPO perspective; as CPOs are the most likely candidate to implement smart charging practices. Nevertheless, this analysis will also show that a broader, multi-stakeholder perspective on the cost-benefits is required that factors in the broader benefits of applying smart charging practices such as Flexpower.

5.1. Cost-benefit categories

The following more structural categories for costs and potential benefits can be discerned for applying Flexpower on public charging stations.

5.1.1. Grid connection costs:

Annual grid connection costs are higher for the 3x35 A grid connection compared to the regular 3x25 A for public charging stations. These tariff groups differ considerably between grid operators in the Netherlands. The price premium of the 3x35 A grid connection can mount up to €400-€700 per charging station (with 2 sockets) on an annual basis.

For the case of Amsterdam an annual addition of around €700 per charging station was applicable in 2019 (€256 for a 3x25 A connection versus €964 for a 3x35 A connection). This adds up to just over €300,000 for all 432 Flexpower charging stations in 2019). This is a significant investment. However, from the start of the Flexpower project it was the intention to explore the possibilities for a new tariff group: 3x35 A with limitations (limitations during evening times). This would allow the higher off-peak power capacity, while retaining limitations in peak hours against a lower grid connection tariff. This complimentary tariff group is still under discussion and is likely an important condition to make Flexpower an attractive option to pursue for CPOs and municipalities.

5.1.2. Transaction costs

No extra operational costs were required for running Flexpower on the charging stations.

5.1.3. Pilot-related costs for implementation

Apart from these more *structural costs* to enable implementing the Flexpower charging profile, this project has incurred some *pilot-related* costs to realize its implementation.

For instance, a manual upgrade of the grid connection to 3x35 A of the 432 charging stations had to be made. This also included changes to the hardware (upgrade the current fuse) as well as software updates (software selectivity for allowing higher current levels). Costs for this manual upgrade accumulated to €45,000-50,000. This translates to around €100-115 per charging station. These one-time costs will likely also apply in case Flexpower is implemented to other existing public charging infrastructure. These costs however are not necessary in case new public charging infrastructure is equipped with the Flexpower option with the appropriate hardware and software from the start.

Lastly, implementing OSCP on the stations required an investment in the range of €20.000-40.000. In case a CPO already implemented OSCP these costs are not applicable; and should be considered as pilot-related.

5.1.4. Amount of Charged Energy

An important question is to what extent Flexpower affected the charge volume per charging stations. The Flexpower 2 project provides ambiguous results on this topic.

Simply looking at the amount of energy charged on Flexpower versus Reference stations, a reduction of around 5% over the period November 2019 to March 2020 was observed: 27.5 kWh/station/day for Flexpower stations versus 29.1 kWh/station/day for Reference stations. This may possibly be explained by the large amount of EVs with 16 A charging capability, as these vehicles cannot benefit from the higher currents provided during off-peak hours but are still limited during the evening hours.

Nevertheless, these results were only derived from a period of 3 months; a longer period may lead to different results. Also, the Reference and Flexpower stations were not randomly sampled, which may introduce a slight bias. From the data analysis we learned that the type of vehicle (and particularly the current limits of the charger in the vehicle) has large effect on the impact of Flexpower on the EV drivers. As such a potential bias as a result of non-random sampling leads to an uncertainty in the results in the order of 5%. The 5% reduction in charge volume may thus be a result of the sampling choices and standard deviation of the results.

One way to circumvent the sampling results is by applying the simulation model and running the exact same transaction set on both Flexpower and Reference stations. The simulation was run and shows how charge volumes on Flexpower stations are slightly higher than Reference stations (31.8 kWh/station/day versus 31.3 kWh/station/day). Also, a simulation of applying Flexpower on a 3x25 A grid connection leads to only minor reductions in electricity charged (31.1 kWh/station/day).

All in all we can conclude that differences in charged volume between Flexpower and Reference stations cannot be established with certainty. It is likely that a selection of 16 A charging EVs will charge slightly less energy (during short sessions in the early evening) but as travel behaviour is likely not influenced, the lower charged volume is likely compensated in later charging sessions. The higher power provided during off peak hours for 25 A and 32 A EVs compensates some of the energy that is not charged by 16 A cars.

Flexpower in the current design is thus not a likely strategy to increase charge volumes per station and as such will have limited effect on the business case of the CPO. On the other hand, charge volumes are not likely to suffer significant reductions due to Flexpower as well, even if the grid connection is reduced to 3x25 A. Since the energy demand is expected to remain stable and because of the buffer effect of the EV battery, energy sales are unlikely to be heavily influenced by smart charging strategies.

5.1.5. Deferred grid investments

The Flexpower project led to a decrease in average power on the Flexpower charging stations of around 1.1 kW/station during peak hours. Assuming that costs of €100 per prevented kW can be claimed then Flexpower prevents an investment of €110 per station. Translated for the complete population of Flexpower stations this mounts up to around €47,000; which is a one-time investment that could be prevented or postponed. Applying Flexpower thus predominantly benefits grid operators. Indirectly the prevented investments in the grid may in time translate to lower grid connection costs for CPOs and households, but this cannot be factored in by CPOs as a potential benefit as a result of applying Flexpower in a business case on short notice.

5.2. Cost-benefit analysis

Table 16 provides an overview of the cost and benefit factors, translated to costs/benefits per station per year in order to compare the order of magnitude of the results.

Most striking is the high grid connection costs that need to be made in order to allow premium charging speeds on off-peak hours. With the current €700/station/year this factor is an order magnitude higher than the other costs associated with Flexpower. Flexpower is likely to lead to limited changes in charging volumes per station; leading neither to financial benefits or costs in the current design of the smart charging profile.

The grid connection costs are also a factor 5 higher than the potential grid deferral costs – although this factor may vary largely between countries and between different networks within countries. As such it is safe to say that a smart charging scheme is most beneficial in cases where electricity networks are weak and investments for providing peak power to allow EVs to charge can be circumvented or postponed with a number of years.

Furthermore, Flexpower is most likely applicable in countries where the cost difference between grid connection is not that high, or in countries where differentiated tariffs can be provided for off-peak and on-peak hours or the tariff group explored (3x35 A with peak limitations) can be applied.

Table 16: Overview of cost/benefit factors for the Flexpower2 project

Category		Per station per year	Variables
1. Structural costs/benefits			
Grid connection costs	€700/station/year (3x25 A → 3x35 A)	-€700	Is known to differ per country. Is currently under discussion in the NL.
Higher transaction costs?	Not applicable	-	This may vary among CPOs (IT backend) and applied charging stations (applied firmware)
Grid deferral costs	1.1 kW per station €100/ kW investment	+€100	Varies per country. Deferred costs likely higher in case of weak networks.
2. Pilot related costs			
Manual changes to charging stations	€45,000-50,000 (for 432 charging stations)	-€100-115	Not applicable for new charging stations.
Changes to backend – implementation OSCP	€20,000-40,000	-€46-92	This largely depends on capabilities of IT system of CPOs.

In conclusion, from a CPO perspective the Flexpower profile provides no direct benefits, which make it difficult to justify relatively high costs for increasing the grid connection to 3x35 A. In order to make Flexpower more attractive the deferred costs for grid investments should be factored in; broadening the scope of stakeholders to include grid operators. The option to allow a new tariff group ("3x35 A with limitations) that is currently explored provides another opportunity of allowing higher charging currents during off-peak times against a lower grid connection tariff, with the limitations during peak hours.

A recommendation is to explore the effects of Flexpower while retaining the 3x25 A grid connection and assess the effects for users. Given that the majority of full electric vehicles do not suffer from this lower grid connection it is likely that the grid benefits for the grid operators may remain while the total costs are reduced significantly.

6. Lessons from the different pilot phases

Flexpower can be divided in two distinct phases. Flexpower1 involved a pilot with 52 public charging stations with a static charging profile (2018); Flexpower2 increased the number of charging stations to 432 And applied a solar-dependent charging profile (2019-2020). Lessons are derived by looking at both of the pilots.

6.1. Preparation and initiation

In the initiation phase an important factor of success was the opportunities a Flexpower profile provided for most partners involved. Liander (grid operator) and ElaadNL (Knowledge and Innovation Centre on Smart Charging; set up by the joint Dutch grid operators) would realize lower grid impacts from charging. The city of Amsterdam might be able to facilitate a better fit of charging profiles with renewable energy (RE) generation profiles, while Vattenfall could potentially benefit from higher earnings (through higher electricity sales). As such all partners had an interest to make this project a success albeit based on different motives and resulting indicators (grid impact, RE generation, business case). Aligning these interests and having the right partners with complimentary competencies on board has been a success factor for continued investment in this pilot by all partners. Future considered steps for Flexpower may encompass including PV generation prediction for profile development, real-time monitoring and switching of smart charging intensity depending on RES generation and EV demand and possibly V2G implementation, building on the partner collaborations established during this initial phase.

The project involved activities to allow running Flexpower charging profiles including (i) upgrading of the grid connection (to 3x35 A), (ii) running the OSCP1.0 protocol to upload and run static profiles, (iii) develop firmware updates of the EV Box chargers, (iv) development of the static profiles and (v) developing more detailed knowledge on the charging behaviour by continued monitoring of the Flexpower (and Reference) stations.

In this project a structured approach and regular meeting schedule was used to allow progress on all aspects of the Flexpower pilot. The SEEV4City project allowed to incur the additional costs for the pilot (e.g. grid connection costs, manual changes to the chargers). All in all, the changes required regarding hardware, software, firmware and underlying protocols (OSCP) were met with several challenges. As such applying Flexpower was not plug & play, but the learnings on how to implement such smart charging profile in practice have been significant, allowing more efficient implementation in future projects.

The project also shows how there are many interdependencies in charging station firmware, backend IT systems by CPO, charging station hardware and protocols applied; which should be analysed upfront to make efficient decisions in the design of the smart charging pilot beforehand.

During the course of the Flexpower1 and Flexpower2 the design of the pilot has shifted several times. Initially six different charging profiles were targeted to allow differentiating between weekdays, weekends, and holidays as well as on weak versus strong grids. In the end it was chosen to focus on applying one static charging profile in Flexpower1 (Flexpower2 also included a solar-related profile); and no distinction was made for weekends and holidays. Given that weekdays are the most intensive in terms of charging point utilization, it was argued that analysing effects on the more strenuous weekdays would suffice to evaluate feasibility also for weekend-days and holidays.

A learning point here is that data analysis of weekday (versus weekend days) provides the legitimization for making such choices and allow a less complex pilot design. Also, for the research setup it is recommended to use random sampling of the stations to enable comparable groups of Flexpower stations and Reference stations. This will facilitate a better academic comparison between the two groups.

6.2. Procurement

Main procurement-related topic relates to the upgrading of the grid connection from 3x25 A to 3x35 A. The additional cost for this upgrade can vary considerably per grid operator and per country. For the case of the City of Amsterdam this upgrade was around €700 per charging station annually (€256 versus €964), which adds considerable annual costs. It therefore forms a significant barrier for upscaling in case the grid related benefits cannot be compensated in some form. Although the grid operator possibly benefits from the use of smart charging, the Dutch Authority Consumer & Market (ACM) regulates the connection cost prices and states that this price must be equal for everyone in The Netherlands. This in contrast to Germany, where capacity and pricing flexibility was used to incentivize the instalment of smart charging units in order to avoid grid reinforcement investments. This form of compensation is currently discussed in the Netherlands; and is likely an important condition for implementing this form of smart charging with higher power during off-peak hours not only in the Netherlands but also in other countries.

The business model for smart charging currently is still more attractive than V2G for the following reasons: (i) technology needed for smart charging is less expensive (ii) V2G currently can be applied to a limited number of EV models on the market, whereas, smart charging can be applied to any EV and (iii) relatively low revenues that are currently achieved by bi-directional charging, depending on the regional tariffs and may need to account for possible battery degradation compensation. Nevertheless, with decreasing costs of bidirectional chargers and increasing opportunities to achieve revenue streams on the energy markets, V2G may still provide value in the mid-long future. Rewards for providing grid services may change when the Feed in Tariffs or electricity tariffs alter in favour of considering V2G services.

6.3. Implementation and installation

Applying the Flexpower smart charging profile required more than a software upload, and several software- and hardware related hurdles had to be taken to implement Flexpower to the point that it was fully operational. This included a manual upgrade of the grid connection, replacement of fuses, and upgrades in the firmware. This was largely carried out by an installation company (Heijmans). Also, some alternations in the backoffice of the CPO were required to allow for communication via the OSCP protocol. For any smart charging pilot that includes changes in the grid connection the costs incurred for manually upgrading the charging stations should be considered.

6.4. Operation of Flexpower

With many different types of EV models on the market, each with different characteristics for charging, the data analysis in chapter 4 shows the importance of understanding the exact charging behaviour of different types of vehicles (number of phases and current limits), as well as the influence of double occupancy on single charging stations. This knowledge allows to understand the actual effects of applying smart charging schemes such as Flexpower for the user, occupancy and utilization, as well as provide inputs on how to optimize the applied profiles.

The data analysis shows how smart charging profiles like Flexpower can reduce the net impact during peak hours with limited negative effects for the user. Opportunities to harness more renewable energy generation were explored but requires further optimization of the charging profile e.g. by reducing charging levels in the morning that allows more daytime/solar charging; allowing more dynamic charging profiles (rather than day-ahead), possibly in combination with supporting incentives.

The cost benefit analyses show that for the CPO the business case for applying Flexpower is limited due to the higher annual grid costs. Allowing reduction of net impact be factored in as an incentive requires rethinking the regulatory context for grid operators in the Netherlands, for instance through enabling differentiation of grid capacity tariffs for off/on-peak hours.

A learning concerns *open standards* which are used for operation of the Flexpower. The OSCP (open smart charging protocol), an open communication protocol between the charge point management system and the DSO, communicates the 24-hour forecast of the available capacity of the electricity grid. This is translated to the OCPP (open charge point protocol) with a charging profile that is sent to all Flexpower charging units. Applying these open standards has allowed to build on existing communication channels and has led to a generic process that can be applied to other contexts using the same protocols.

An important learning relates to developing sufficient monitoring capability for the pilot partners. Given that communication via OSCP and applying smart charging profiles is still in its infancy, monitoring to what extent profiles are actually run on Flexpower charging stations, possible effects on charging behaviour on different vehicles types and impact on the firmware of the charging stations itself needs to be carried out to establish any errors. Through efficient monitoring these can be tackled.

It also pays to communicate benefits for EV drivers. For example, when taxi drivers learned that the Flexpower charging units are capable of charging with more power outside peak demand periods during the day they started enquiring at the municipality office about where they could find these FlexPower charging units.

7. Conclusions and Recommendations

This report of the Operational Pilot Flexpower2 presents the results of applying a time dependent capacity profile, including a current limit in peak hours and a current surplus during off-peak hours. The following conclusions and recommendations can be drawn.

7.1. Conclusions

7.1.1. Understanding charging behaviour & monitoring

This research has led to a deeper understanding in the factors that influence the charging speed of EVs under different circumstances.

Large differences were found between the theoretical charging limit of charging stations and the practical charging speed that was realized. For 1x16 A vehicles the actual charging speed is stable around 3 kW, while the theoretical limit for 1x16 A is 3.7 kW, a difference of about 20%. This discrepancy can be found for all categories and is an important insight to help make policy and models more realistic.

This difference between theoretical limit and the charging speed in practice arises from a combination of vehicle, station and grid related factors. It is difficult to say to what extent this result applies to different cities and countries as the local circumstances may differ significantly for public charging infrastructures in terms of connection types, vehicle fleet composition and occupancy rates.

7.1.2. Effects of Flexpower

The Flexpower2 pilot has shown that it is possible to limit the energy consumption during peak hours with a relatively small impact on EV drivers. In total 91% of all charging sessions were not affected in terms of charged energy, with only 6% of all sessions being negatively affected (the vehicles battery is less full with Flexpower profile than with Reference one) and 4% being positively affected (more energy charged). As such the Flexpower2 charging profile is a viable solution for balancing the load on the electricity grid particularly if higher current levels are provided during off-peak hours.

The group of consumers with the most negative impact are PHEV models which have a good alternative in the form of their combustion engine. Advanced BEV models with higher charging speeds are likely to profit from the Flexpower profile. With a PHEV-dominated fleet composition in the Netherlands (and in this pilot), the results may be more positive for countries that have a higher share of BEVs (compared to PHEVs).

Since the consumer impact of Flexpower is positive specifically for 3-phase full electric vehicles with high charging speeds, the potential for applying this measure will increase further as the fleet composition will move to vehicles that charge faster (higher current levels and/or more phases).

The current one-size-fits all Flexpower implementation is already suitable for large-scale roll out. As such it is recommendable for policy makers in cities with a high take-off of EVs. Applying smart charging profiles such as Flexpower offers cities large scale integration of EVs while reducing concerns on grid impact and minimizing effects on the user.

Based on the current Flexpower profile an average reduction of 1.1 kW per charging station was realized. This would translate to avoided grid investments of around €47,000 for the population of 430 charging stations for strengthening the grid on the long term. Given that Flexpower can be upscaled in theory it can contribute to a significant reduction of grid investments in the future where EVs are likely to become more mainstream. The application of a time dependent profile should be implemented first in areas with grids that are considered the weak spots (with limited capacity space) within the grid infrastructure.

The pilot was carried out on public chargers, but the results may also apply on reducing grid impacts of residential charging, although policy makers currently have little influence on charging levels on residential level.

Regarding the match with renewable energy generation, the results show that in the current situation, the demand is already fulfilled with the low current limit during the day, which negate the effects of a higher current limit. More dynamic profiles, more stringent current limits in the morning and consumer incentives may improve the match with renewable energy generation.

7.2. System Recommendations

The following recommendations can be made based on the Flexpower pilot.

A **dynamic approach** would offer an optimal consumer service and more flexibility than the current static time-dependent profile. For example, a limit could be imposed on an area serviced by a single transformer, and only when the sum of all sessions passes this threshold charging speed can be regulated accordingly. This avoids unnecessary speed reduction and requires real time communication between the DSO, CPO and the charging infrastructure. This can be supported by both the OSCP and OCPP protocol but is not currently in place.

A second possible improvement on the current one-size-fits all implementation is to grant control to the **consumer**, possibly combined with a price incentive. It may be favourable to use consumer inputs rather than complicated and incomplete predictive models instead. Depending on the estimated connection time and amount of required energy an optimal profile can be calculated. This avoids the effect of impacting vulnerable charging sessions but is likely to reach almost the same overall effect. An experiment has been done with a 'stop button' in Gelderland and preliminary results show that it is not misused to circumvent the charging limitations.

The current implementation of Flexpower leads to a **rebound peak**. This is not necessarily a problem since the load of all other connections may have reduced sufficiently by the time current limitations are lifted, but it is not necessary and could be avoided by applying a more gradual increase in the current limit after peak hours. It is recommended to explore the opportunities of reducing rebound peaks by designing more gradual increase in charging speed after the off-peak limit.

The results of the pilot show how the higher annual **grid connection costs** reduce the business case for Flexpower and as such may hamper the large scale introduction of Flexpower. It is recommended to further analyse the impact of Flexpower on users and energy consumption on the regular grid capacity of 3x25 A, as first simulation results suggest that switching back to a 3x25 A connection has limited effect on charged energy with actual EV population dominated by 1x16 A vehicles. The picture might change with the larger adoption of 3 phases vehicles.

7.3. Policy Recommendations

7.3.1. Key messages

Based on the results achieved from the Amsterdam Flexpower 2 pilot, the following ***key messages*** were derived:

- The Flexpower smart charging profile enables reducing charging demand during peak times with limited impact for users of the charging infrastructure. In the test carried out, around 6% of the charging sessions were labelled as negatively affected. In the majority of cases this concerns PHEVs which are equipped with an internal combustion engine and as such will not suffer negative impact in terms of range.
- By applying Flexpower the power demand during peak demand (in evening times) was reduced by on average 1,1 kW per charging station (50% of the total load). This translates to avoided grid investments of around €47.300 for the current pilot test. Given the scalability opportunities smart charging practices such as Flexpower provide a powerful strategy to reduce grid investments that may occur as a result of EV adoption in the future.
- In order realize a better match between renewable energy generation on the one hand and daily charging behaviour on the other a more optimized charging profile should be designed (including a morning reduction charging speed) possibly in combination with incentives for EV drivers and application of more dynamic charging profiles.
- Proper assessments of the impact of smart charging practices on EV users requires a detailed understanding on the charging characteristics of different EV models as well as the impact of double occupancy on charging speeds. The charging station **simulation model** developed in this project provides a generic and validated model for making detailed estimations of charging behaviour on a population of charging stations with different sets of vehicles. It can be used to model the effects of particular smart charging profiles beforehand and evaluate possible effects on users, energy charged and net impact.

7.3.2. Policy suggestions

The following ***policy suggestions*** are provided to enable a smoother transition into a smart and clean electrification of transportation.

- Data availability and transparency for better integration of electric transportation at all levels.

  A necessary condition for carrying out the data analysis has been the availability of data on charging transactions including meter values to actually evaluate charging behaviour of vehicles. Enabling data analysis is a strong enabler of research that may support both optimizing the chosen smart charging profiles as well as provide legitimization of chosen policies towards EV drivers.

  Transparency of charging speeds towards EV drivers is considered an important condition of success of Flexpower or other smart charging practices in order to create understanding and buy-in from users.

- Standardization and communication protocols to allow interoperable smart charging and V2G

  Flexpower requires open protocols like OCPP (open charge point protocol) and OSCP (Open smart charging protocol). Similarly charging stations should be made "smart charging ready" amongst others by including smart meters and firmware that enables applying these protocols. Policy makers involved in electric vehicle policies should include smart charging requirements in tenders for public charging stations. Finally, the IEC 61851-1 needs to be better implemented and tested by the vehicles manufacturers to allow discontinuity in the charge cycle.

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